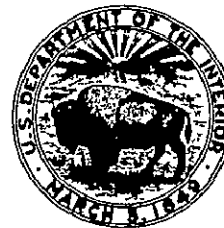


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY



PROJECT REPORT
Colombia Investigations
(IR)CO-36

A SHORT COURSE ON MINERAL EXPLORATION, MINE DEVELOPMENT AND
MINERAL PROPERTY EVALUATION



Prepared on behalf of the
Government of Colombia and the
Agency for International Development
U. S. Department of State

A SHORT COURSE ON MINERAL EXPLORATION, MINE DEVELOPMENT AND
MINERAL PROPERTY EVALUATION

By

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This report is preliminary and has not
been edited or reviewed for conformity
with Geological Survey standards
or nomenclature

MINERAL EXPLORATION

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INTRODUCTORY STATEMENT

In July of 1975, as part of activities covered by PASA LA(IC) 40-71, Loan 512-L-058, DRA4-DA010, H. R. Carpenter, R. W. Hutchinson, D. W. Gentry, and Alfred Petrick, Jr., of the U. S. Geological Survey, visited Bogotá, Colombia, to present a 3-week series of lectures in mineral exploration. The Instituto Nacional de Investigaciones Geológico-Mineras (INGEOMINAS) requested the training course, and the work was sponsored by the Government of Colombia and the Agency for International Development, U. S. Department of State. This manual was developed for use in the class work and field trips; the course work, at post-graduate level, covered environments of mineral formation, ore genesis, evaluation of mineral deposits, mineral processing, and development of mineral deposits for production.

Success in mineral exploration depends on a thorough understanding of the total environment in which a mineral deposit has formed and the modifications which this deposit has undergone since its formation. Knowing its genesis under the time-space concept, an exploration team is cognisant as to where and how to search for the new orebody.

For this reason geologic environments in which major ore deposits of the world have formed will be emphasized at the beginning of this symposium. These discussions will be followed by a brief analysis of exploration planning and execution and a summation of a successful porphyry copper exploration program on the Papago Indian Reservation in Arizona.

A SHORT COURSE ON
MINERAL EXPLORATION, MINE DEVELOPMENT AND
MINERAL PROPERTY EVALUATION

- BOGOTA - COLOMBIA

INTRODUCTION

The objective of this course is to present in summary fashion the most recent concepts and applied thinking in mineral exploration, mine development, and mineral property evaluation to individuals responsible for the discovery, development, and economic analysis of new mineral properties.

Dr. Carpenter and Dr. Hutchinson will lead a field trip from June 23 - 28. From June 30 - July 7, both professors will lecture on mineral deposits geology and mineral exploration. This material will include the broad aspects of evolutionary metallogenic development of mineral deposits and their host environments, formulating an exploration program, its execution and evaluating its results, and a description of a porphyry copper exploration program which resulted in the discovery of a major orebody. During the following two weeks lectures will be given by Dr. Gentry on mine development and Dr. Petrick on the evaluation of mineral properties. Fundamental concepts in resource evaluation, cash flow, rate of return, Hoskold and Morkill formulas and cost in price estimates in property valuation will be discussed.

GEOLOGIC ENVIRONMENTS IN WHICH MAJOR ORE DEPOSITS HAVE FORMED

VOLCANOGENIC ENVIRONMENT

A large number of massive, base metal sulfide deposits formed in major sea floor basins within and in the near vicinity of volcanic piles and cones during the Archean. These include the billion dollar Noranda and Kidd Creek deposits of northern Quebec and Ontario as well as numerous others (Plate A).

They are closely related in time and space to the development of thick Archean volcanic piles. The ores were deposited from a fluid phase (brine) generated during volcanism, probably by mixing and circulation of sea water which had been trapped in and modified by reaction with the volcanics. Metals leached by this brine from the host volcanic rocks were carried as chloride complexes, migrated upward to sites favorable for deposition within the volcanics and were deposited in fumarolic vents, either within the volcanics below the rock surface or on this surface with the adjacent turbidites, graywackes and sea floor muds (Plate B). The volcanic centers in the Archean are well stratified with basalt at the base as a platform. Andesites occupy most of the middle and upper parts of the cone. Felsic volcanics and intrusive plugs occur in the upper fringes. (Plate B')

Most of the massive sulfide deposits have formed in this upper, felsic zone and outward in the graywacke and shale transition zones. Metal-bearing ferruginous chert marker beds are important ore indicators because they formed immediately above or outward from the orebodies on the then existing sea floor. Gasses and fluids from the forming orebodies are believed to have supplied the silica and iron for these ferruginous sea floor oozes. Some of these horizons are tens of feet in thickness and extend outward for twenty or more miles from the volcanic source fumaroles. They exhibit prominent facies changes from sulfide (pyritic) to carbonate (sideritic), oxide (magnetitic), and silicate (Fe-chlorite) varieties. Some are mined as iron deposits.

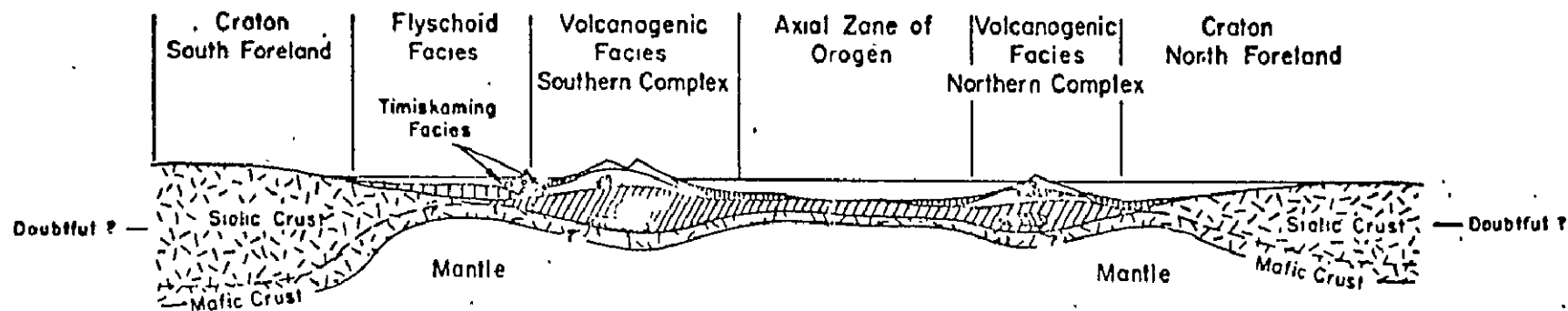
Massive and disseminated nickel sulfide orebodies with low copper content also occur with ultrabasic flows, sills and dikes which were derived from the ancient Archean mantle and form part of the pillow lava basaltic platform (Plate B).

The mineralization frequently is zoned in the volcanic piles with massive or disseminated pyrite-chalcopyrite orebodies within the volcanic center and zinc-copper orebodies at higher stratigraphic levels and outward toward the graywacke fringe. Massive lead-zinc-silver orebodies of Proterozoic age formed by similar processes but further from fumarolic vents in the sea floor black shales. Similar, vertical zoning is evident in some of the volcanic centers as well. Also, somewhat later gold-quartz veins have formed at various levels in the Archean volcanic successions, sometimes in the lower mafic basaltic platforms, sometimes near the crest in the rhyolites. They appear to be the result of mobilization of gold and silica deeper in the volcanic pile. (Plate B' to B'').

The volcanogenic environment changed in character with time. In the

SEA FLOOR VOLCANIC PROFILE

ABITIBI OROGEN (NORANDA-TIMMINS ZONE)

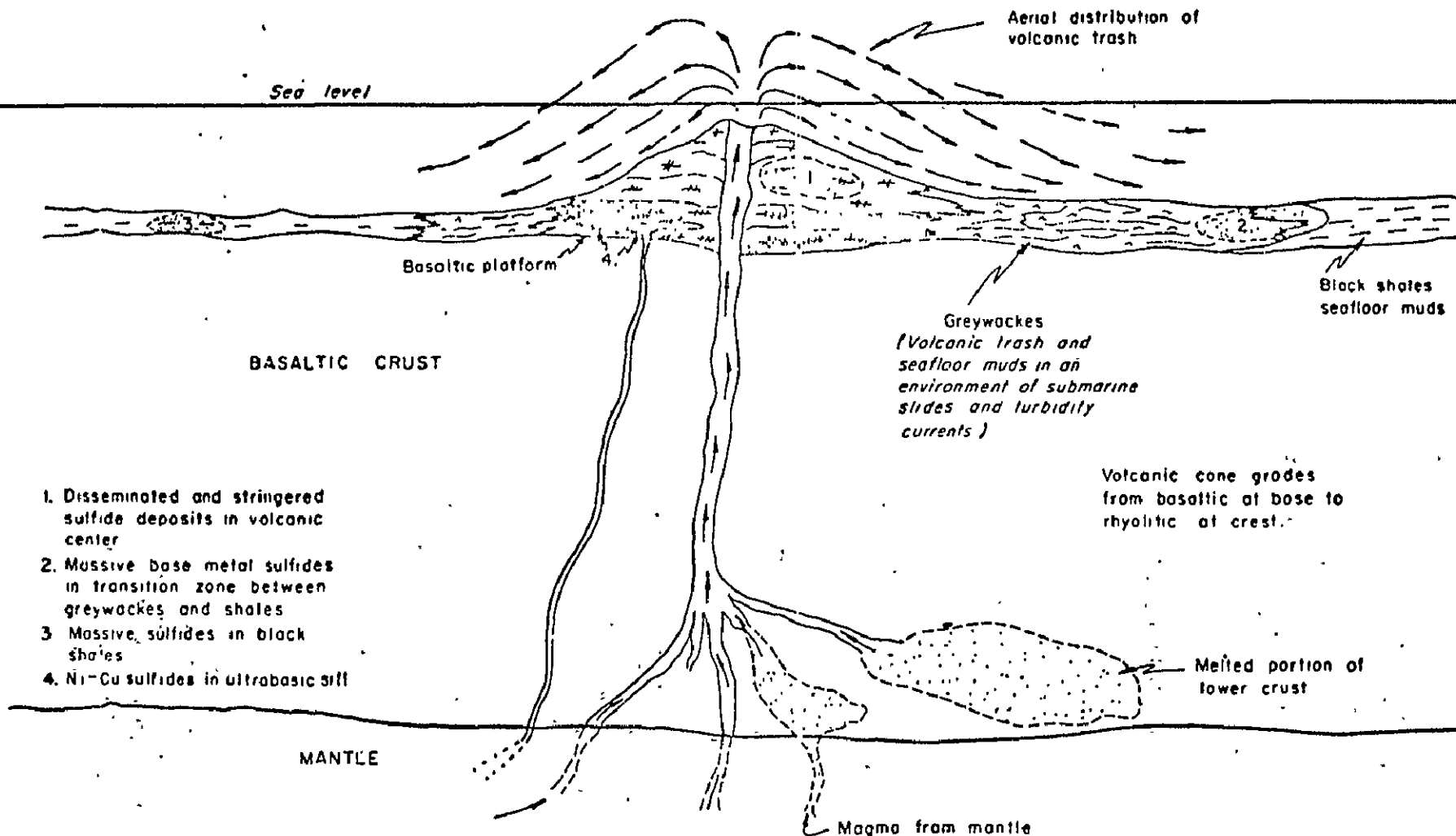


EXPLANATION

- | | | | |
|--|--|--|----------------------|
| | GREYWACKE, ARGILLITE | | BASALT |
| | GRANODIORITE | | GABBRO, ANORTHOSITE |
| | DACITE, RHYOLITE | | GABBRO, NORITE, etc. |
| | ANDESITE | | VOLCANICLASTICS |
| | CONGLOMERATE, GREYWACKE; SOME TRACHYTE | | |

Approx 100 miles

SEA FLOOR VOLCANIC ENVIRONMENT (GENERALIZED SKETCH)



Proterozoic and Phanerozoic the volcanic piles are more complex petrologically and mineralogically. They have formed both as pillow lavas along the sea floor spreading zone and along the subduction zone of the plate tectonics mechanism (Plates C, D, and E). Such volcanic piles include the Ordovician deposits in New Brunswick, in Devonian volcanic centers in Spain and Portugal, Cretaceous deposits on the Island of Cyprus, Turkey, and in Oman on the tip of the Saudi Arabian peninsula, and in the upper middle Miocene of Japan and the Philippines. They are discussed briefly in the following section.

ENVIRONMENTS RELATED TO THE PLATE TECTONICS MECHANISM

OCEANIC RIDGE

Pyrite-copper orebodies have formed and are forming under volcanogenic conditions within and along the flanks of the sea floor spreading zones such as the Mid-Atlantic Ridge, the axial trough of the Red Sea, the East Pacific Rise, the Indian Ocean ridge and similar belts. The Cyprus pyrite-chalcopyrite ore bodies consist of up to 99 percent combined sulfides with 2 to 4 percent copper. They formed within local sea floor depressions in the basaltic pillow lavas in the Tethys seaway during Cretaceous time. Fluids rising from magma sources at depth are believed to have supplied most of the metals. They range up to 20,000,000 tons (Plates C and D). Deposits of this size and grade are extremely attractive exploration targets. They are distinctive of ophiolitic (oceanic crustal) rocks of Mesozoic-Tertiary age. Because rocks of this age and type occur in Colombia these deposits merit special attention here.

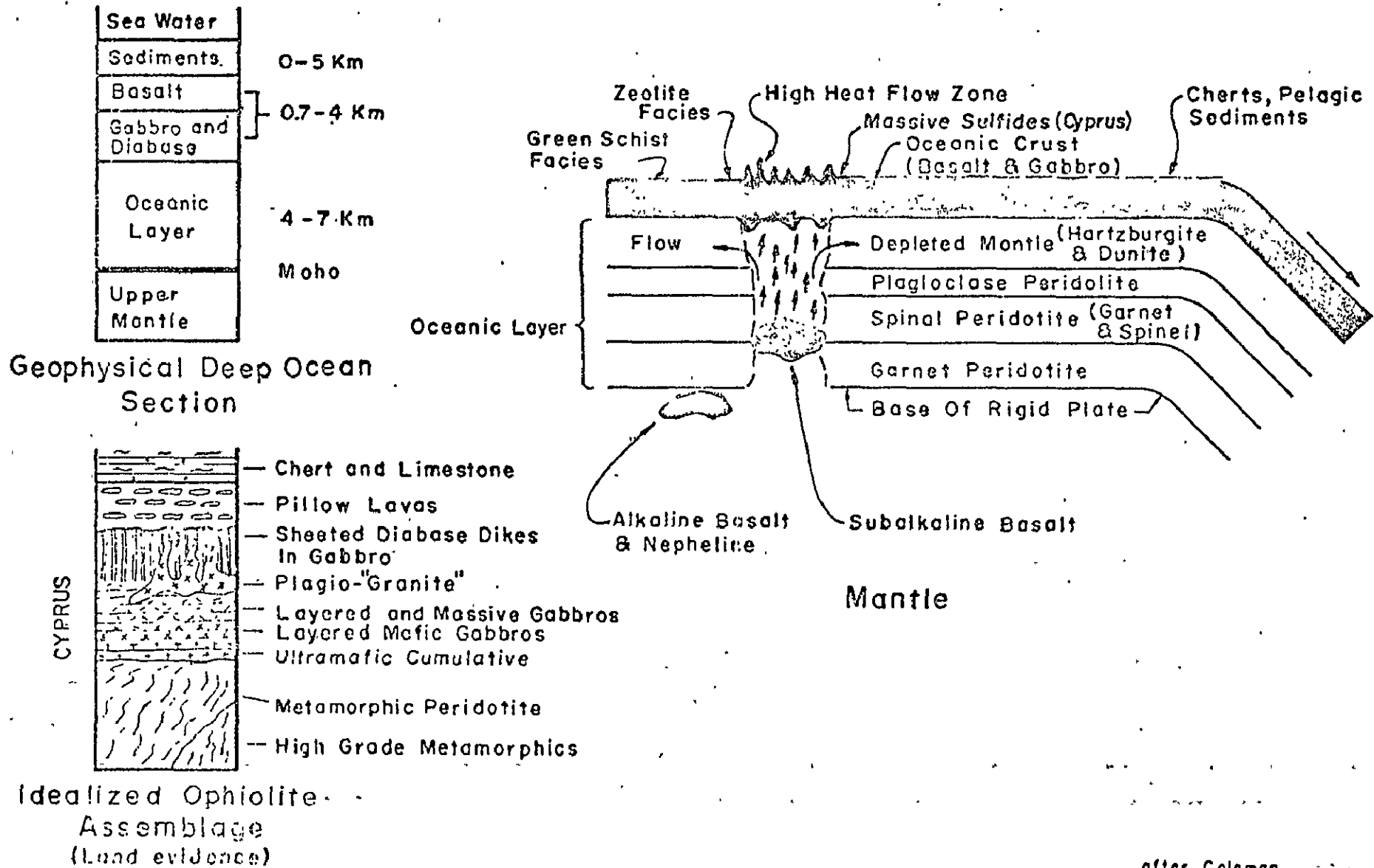
Nickel-copper orebodies also have formed in the ridge environment in association with ultrabasics which intruded the gabbros, diabases and basalts of the upper fringes of the oceanic crust. These orebodies are both massive and stringered and are similar to those which occur in the basalt platform of the Archean volcanogenic environment.

SUBDUCTION ZONE

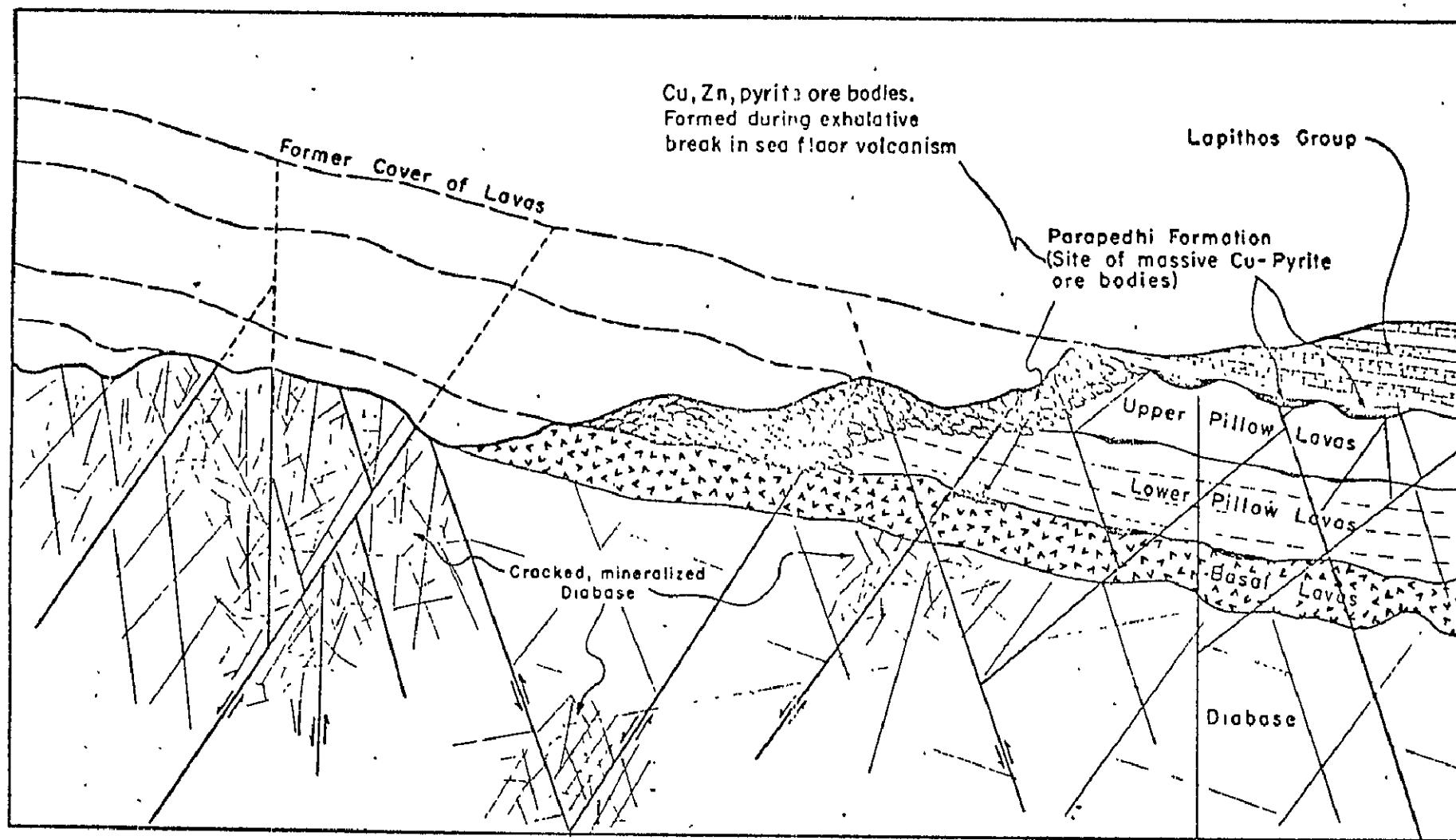
Many different types of mineral deposits are associated with the overall subduction phenomenon including copper and/or nickel sulfides in the trench and melange zone associated with ultrabasic intrusives, Kuroko type massive sulfides both in the outer basin and along with porphyry copper and base metal veins and replacement deposits in the volcanic arc, and lower temperature gold, silver, antimony and mercury deposits above and outward from the porphyry centers. Oil accumulations may occur in the inner basin in structural or stratigraphic traps (Plate E).

All of these deposits are the result of disequilibrium conditions developed as a result of upwelling of magmas and fluids along the oceanic ridge (Plate D) and the subduction of the resulting oceanic sediments and crust beneath the adjacent, overthrust block. Partial melting has occurred at and below 100 kilometers along the subduction zone, and the lighter, melted fractions of the sediments, oceanic crust and mantle are believed to have risen, incorporated portions of the overthrust, lower parts of

OPHIOLITE SEQUENCE OF THE OCEANIC CRUST



after Coleman

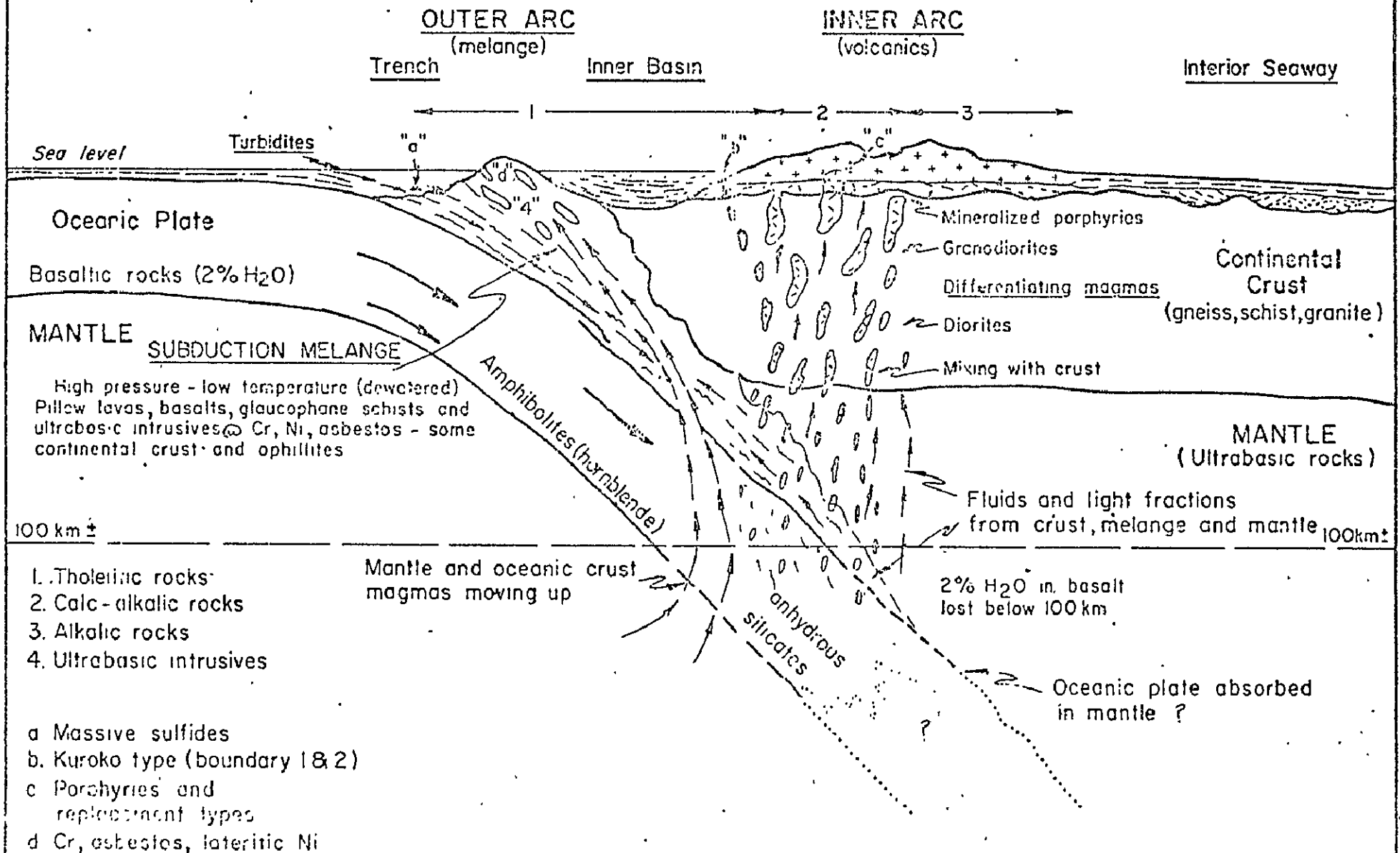


0 1000 2000 3000 4000

SCALE

IDEALIZED CROSS SECTION SKETCH ILLUSTRATING ENVIRONMENTS OF CYPRUS
COPPER-PYRITE DEPOSITS

GENERALIZED SKETCH OF SUBDUCTION ZONE



the sialic crust to form batholiths of dioritic composition. These in turn have risen through the continental crust, differentiated to granodiorites, monzonites and granites. Dikes from these intrusives have served as feeder channelways to develop volcanic piles and a chain of volcanos such as those in the Andes, Japan and Java. The volcanic necks and stocks often have served as collecting centers for fluid phase water, volatiles and gases from the magmas to form porphyry ore bodies. The fluids are often highly saline and have transported metals to sites favorable for deposition. Both metals and salts are believed to have been derived largely from altered sea floor basalts of the mid-ocean ridges, and were transported to the subduction zones by the plate tectonic mechanism. These sea floor pillow basalts are anomalously high in metal content (Table I).

The subduction zone mineral deposits are described briefly as follows:

Massive Sulfide Deposits of the Trench Zone.- These may be of three types: transported massive sulfide deposits from the oceanic ridge environment, massive sulfide deposits associated with ultrabasic rocks intrusives into the melange zone, or massive sulfides which formed in a volcanic pile superposed on the melange. This latter volcanogenic environment is similar to the Archean. In some instances nickel-bearing ultrabasic rocks have intruded the melange as well to yield lateritic nickel deposits upon uplift, erosion and weathering (Plate E).

Kuroko Type Massive Sulfide Deposits of the Outer Basin.- These deposits, which occur in Japan and the Philippines, have formed over the crest of and adjacent to rhyolite domes which have intruded the sea floor of an embayment. High grade lead, zinc and copper orebodies developed in the crest of the dome and in the adjacent spalled breccias. They range from small to very large and are high grade deposits; they often occur in swarms around a group of sea floor rhyolite domes. They are believed to be partly diagenetic and partly epigenetic in origin (Plate G).

Porphyry Copper-Molybdenum Deposits of the Volcanic Arc.- In the southwestern United States and in the Andes these mineralized "porphyries" occur largely as multiple intrusions of monzonite to granite composition as a result of differentiation in the underlying sialic crust. They usually are porphyritic in texture (Plate H). In the oceanic areas where sialic crust is thin or absent the "porphyries" are dioritic to granodioritic in composition and often are non-porphyritic. (Plate F).

Alteration and mineralization are well zoned in most porphyry deposits of the southwestern U.S. This zoning is illustrated on Plates I and J. Both zonal patterns are interpreted to be a result of decreasing thermal and pressure gradients together with mixing with meteoric waters and other factors influencing the chemistry of the system. These halos are critical in locating and evaluating exploration targets.

In some instances deep erosion has removed the porphyry hood zone above a batholith to expose strong vein systems along the contacts of the batholith. The Mother Lode gold veins along the western fringe of the Sierra Nevada batholith in California and the tin-tungsten veins and stockwork systems adjacent to batholiths in the eastern Andes of Bolivia are examples.

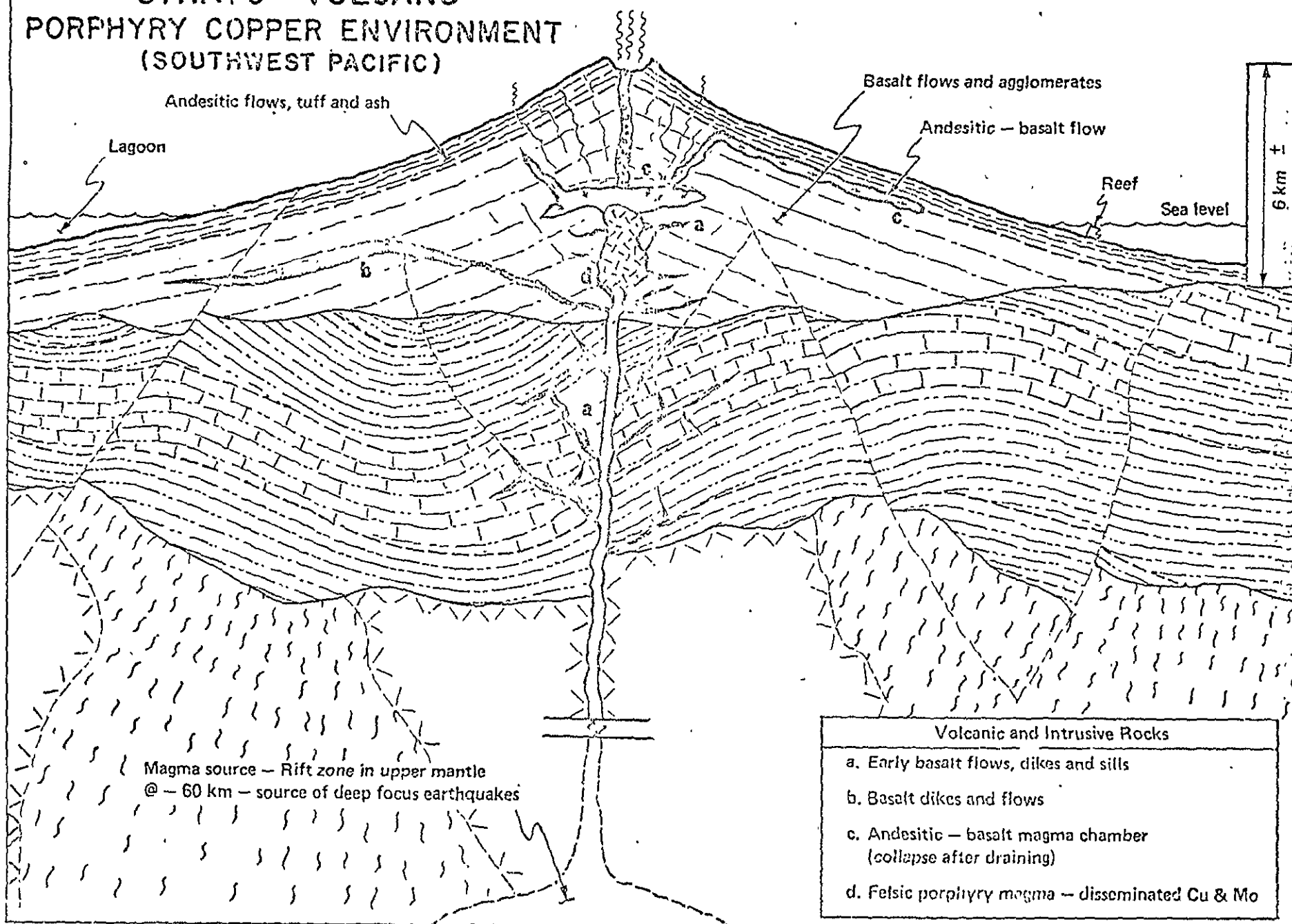
GOLD

Table 79-E-2...Average^a values for igneous rocks (based on data of Table 79-E-1)

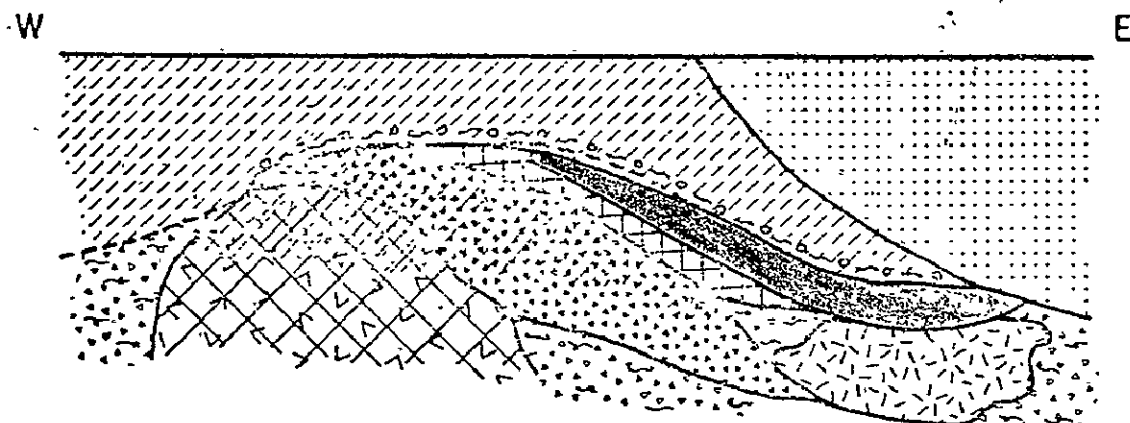
ROCK TYPE	NUMBER OF ANALYSES	WEIGHTED AVERAGE, ALL ANALYSES
<i>Plutonic rocks</i>		
<i>Salic</i>		
Granite	310	1.7
Granodiorite	380	3.0
Aplite (including dikes and veins of granite and greisen)	23	4.2
<i>Intermediate</i>		
Diorite, quartz diorite, monzonite, quartz monzonite, tonalite	261	3.2
<i>Mafic</i>		
Gabbros (including gabbro-diorite).	580	4.8
<i>Ultramafic</i>		
Mainly dunite and peridotite	149	6.6
<i>Volcanic and hypabyssal rocks</i>		
<i>Salic</i>		
Mainly rhyolite (including rhyodacite, dacite felsite, latite and obsidian)	188	1.5
<i>Mafic and intermediate</i>		
Mainly basalt, andesitic basalt, andesite (51) trachyandesite and trachyte (2)	696	3.6

^a A few values considered anomalously high are omitted in the calculation of average values. The include the following: DeGRAZIA and HASKIN (1964): perlite 21 ppb; KUSHMURADOV (1970): granite 6.1 ppb and diorite 17 ppb; MOISEENKO et al. (1971): small stocks of the Tokur district 28.3, 26.0, 67.2 ppb; SHILIN (1968): granite 15 ppb and granodiorite 20 ppb.

STRATO - VOLCANO PORPHYRY COPPER ENVIRONMENT (SOUTHWEST PACIFIC)



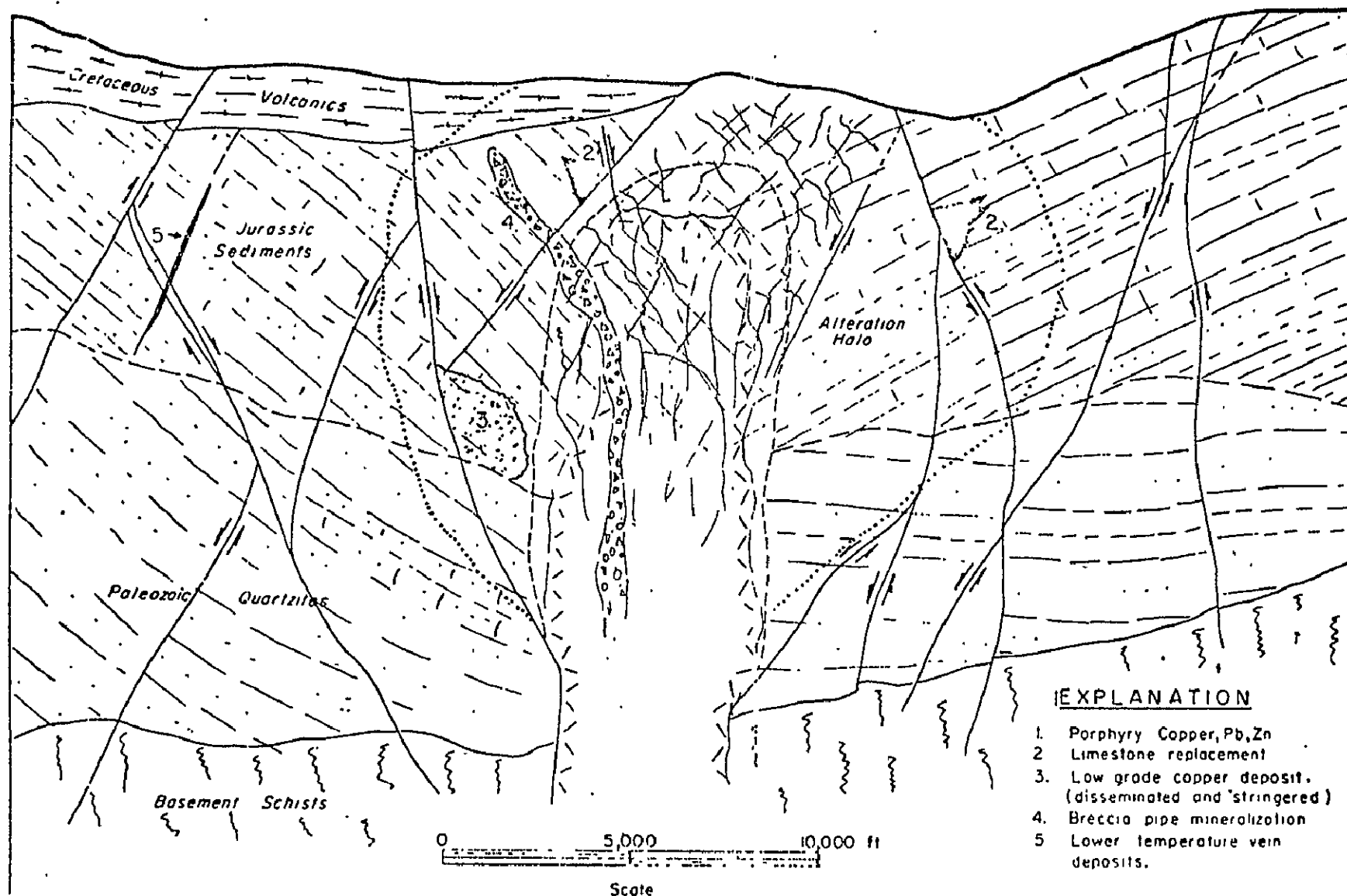
IDEALIZED PROFILE OF THE UCHINOTAI ORE DEPOSITS



Explanation

-  YOUNGER RHYOLITE
-  AKAMORI TUFF (PUMICE TUFF)
-  FERRUGINOUS CHERT (MUDSTONE 2)
-  BARITE ZONE
-  BLACK ORE - Kuroko
-  YELLOW ORE - Oko
-  SILICEOUS ORE - Keiko
-  GYPSUM ORE
-  MOTOYAMA VOLCANIC BRECCIA (EXPLOSION BRECCIA)
-  WHITE RHYOLITE
-  UWAMUKI TUFF BRECCIA (PYROCLASTIC FLOW)

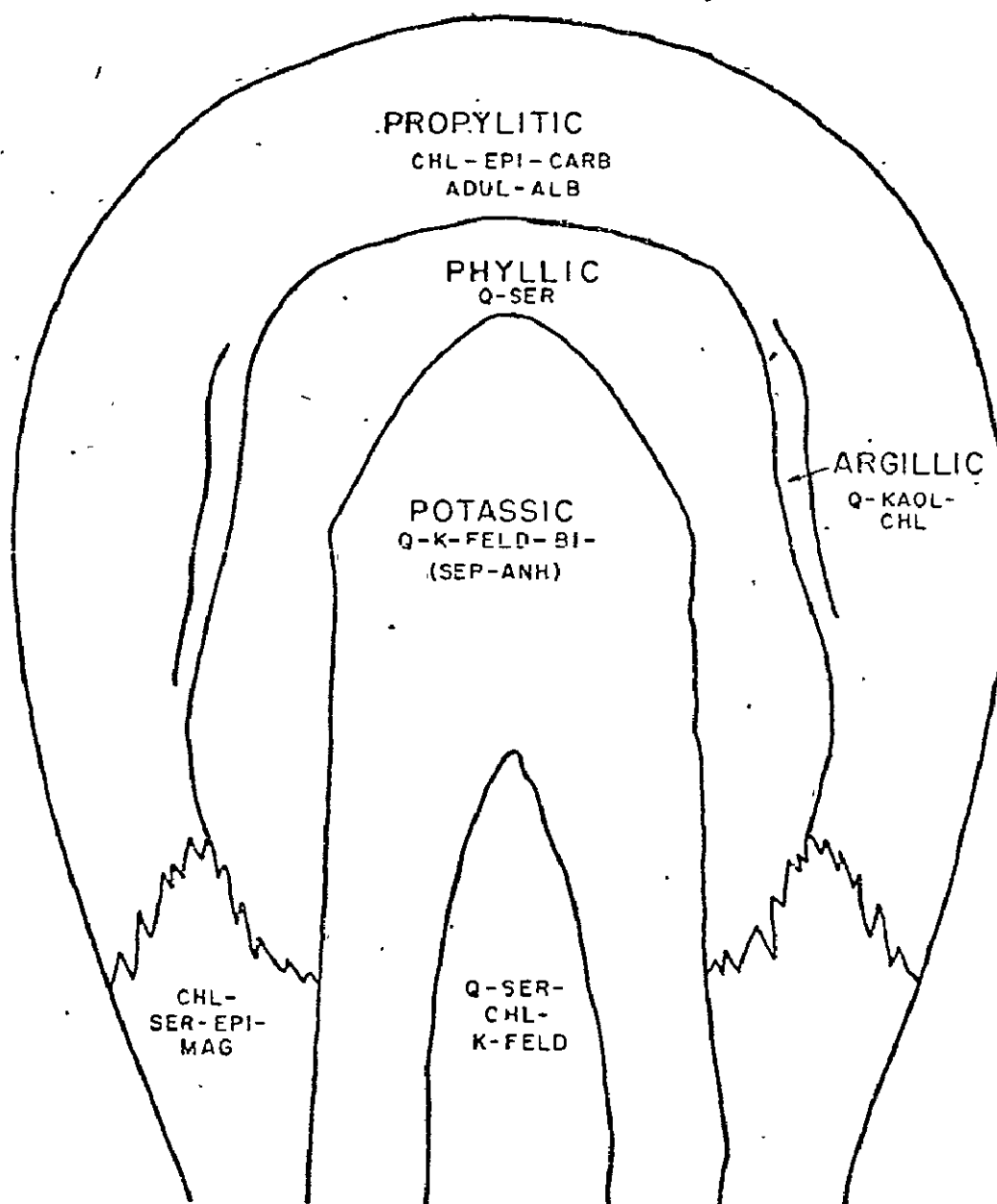
GENERALIZED SECTION ILLUSTRATING MINERALIZATION IN AND NEAR A PORPHYRY INTRUSIVE



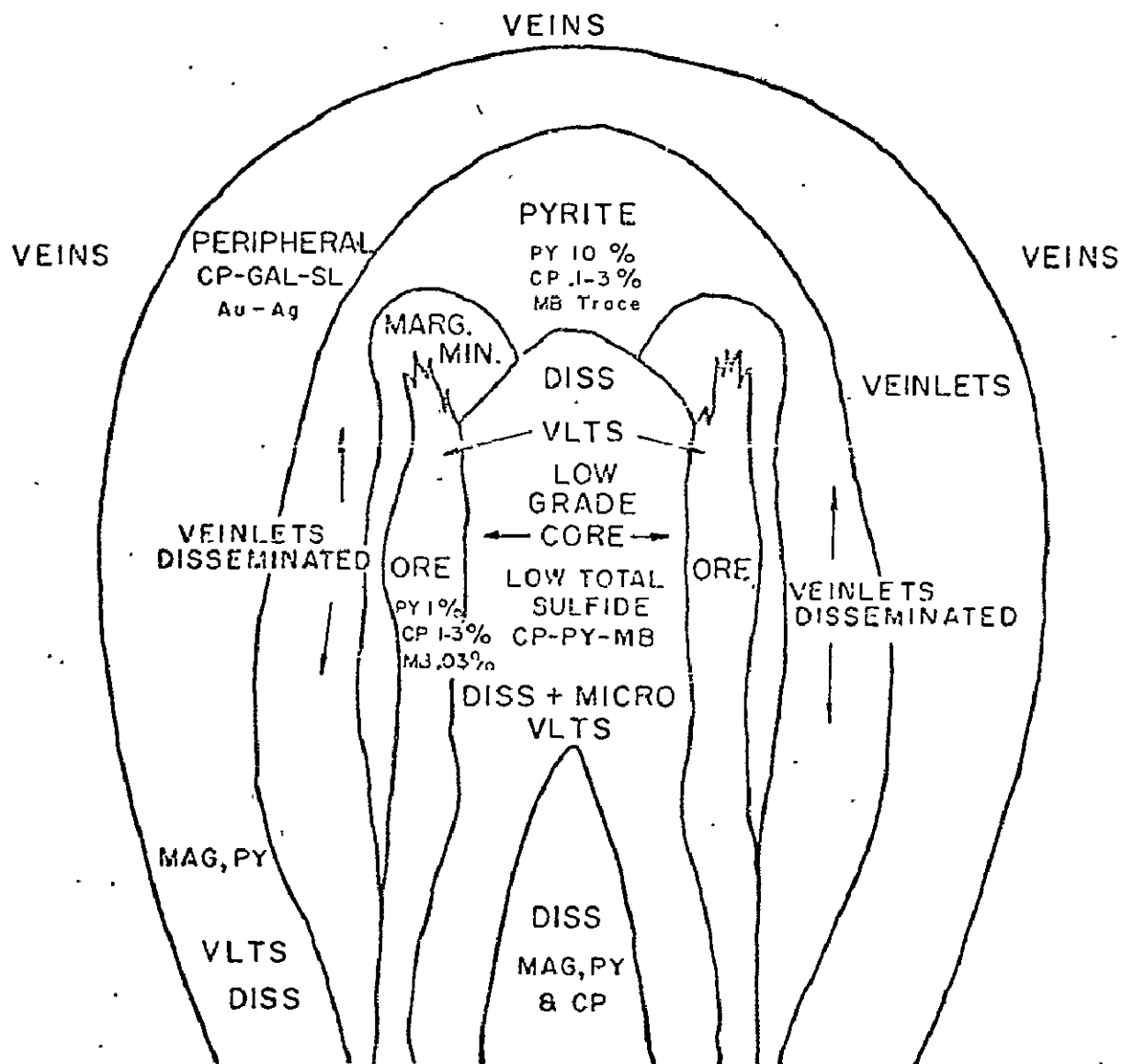
EXPLANATION

1. Porphyry Copper, Pb, Zn
2. Limestone replacement
3. Low grade copper deposit, (disseminated and stringer)
4. Breccia pipe mineralization
5. Lower temperature vein deposits.

PORPHYRY COPPER CROSS SECTION ALTERATION HALOS



PORPHYRY COPPER CROSS SECTION MINERALIZATION ZONING



PORPHYRY COPPER ENVIRONMENT SOUTHWEST PACIFIC

Recent studies of porphyry copper deposits discovered in Papua and the islands of the New Britain and New Ireland chains to the northeast have clarified the genesis of these deposits considerably.

Plate F illustrates the third dimension relationships in the strato-volcanic environment in which the porphyry copper deposits have formed. They developed late in the volcanic-igneous sequence, the steps of which are listed as follows:

- a. Early basalt dikes, sills, flows and aerial debris to form the initial cone.
- b. Additional eruptions of aerial debris together with sills and dikes cutting the cone, and breaching the flanks to form surface flows.
- c. Further eruptions of ash, breccia, tuff and agglomerate and the formation of a magma chamber which causes expansion of the upper cone. A flow develops when the magma breaches the flank. Loss of magma causes the chamber to collapse.
- d. Differentiation of magma at depth to yield andesitic basalts and andesites which form the final cover of the strato-volcano. These magmas are sticky, the volcanic neck freezes, and a diorite intrusive stock forms. It is cracked by intrusive stresses, and is mineralized by the accompanying fluid phase to form a porphyry copper deposit. Mineralization may extend outward into the volcanics, or into the underlying rocks if the stock forms beneath the cone.

This model was developed by Dr. Collin Branch, Head of the Technical University at Adelaide in Australia after two years of seismic research at Rabaul, New Britain and the geologic study of porphyry copper deposits in the region.

Recent porphyry copper discoveries in the southwest Pacific have been made in deeply eroded strato-volcanos, similar to the above example where dioritic to granodioritic stocks are exposed. The andesitic volcanics around the edge of the eroded cone contain anomalous copper and molybdenum which indicated the low grade copper-molybdenum deposit in the neck.

CRATONIC IGNEOUS MOBILIZATION

There are major mineral deposits closely associated in time and space with volcanic and igneous centers well within the continental cratons which are not directly associated with either crustal spreading or subduction zones. The Colorado Mineral Belt is an example.

Climax, Henderson and other molybdenum-bearing porphyries occur along this zone as well as many base metal, gold and silver districts such as Silverton, Crested Butte, Montezuma and Idaho Springs. Deep seated crustal failure accompanied by mobilization of the sialic crust has resulted in the formation of batholiths and

stocks and the accompanying mineralization. Two ages of igneous activity and mineralization are evident, Laramide and mid-Tertiary. These correspond roughly with plate subduction of the California coastal fringe and the overriding of the East Pacific Rise by the westward moving North American continent.

Except for a lack of copper these molybdenum porphyry deposits are very similar to the porphyry copper deposits of the southwest U.S. They are multiple intrusive in character, have well developed alteration halos, and the mineralization occurs in stringers and along joint surfaces. Vein and replacement type mineralization along the Colorado Mineral Belt also is similar to that found in the Arizona and in the Andes.

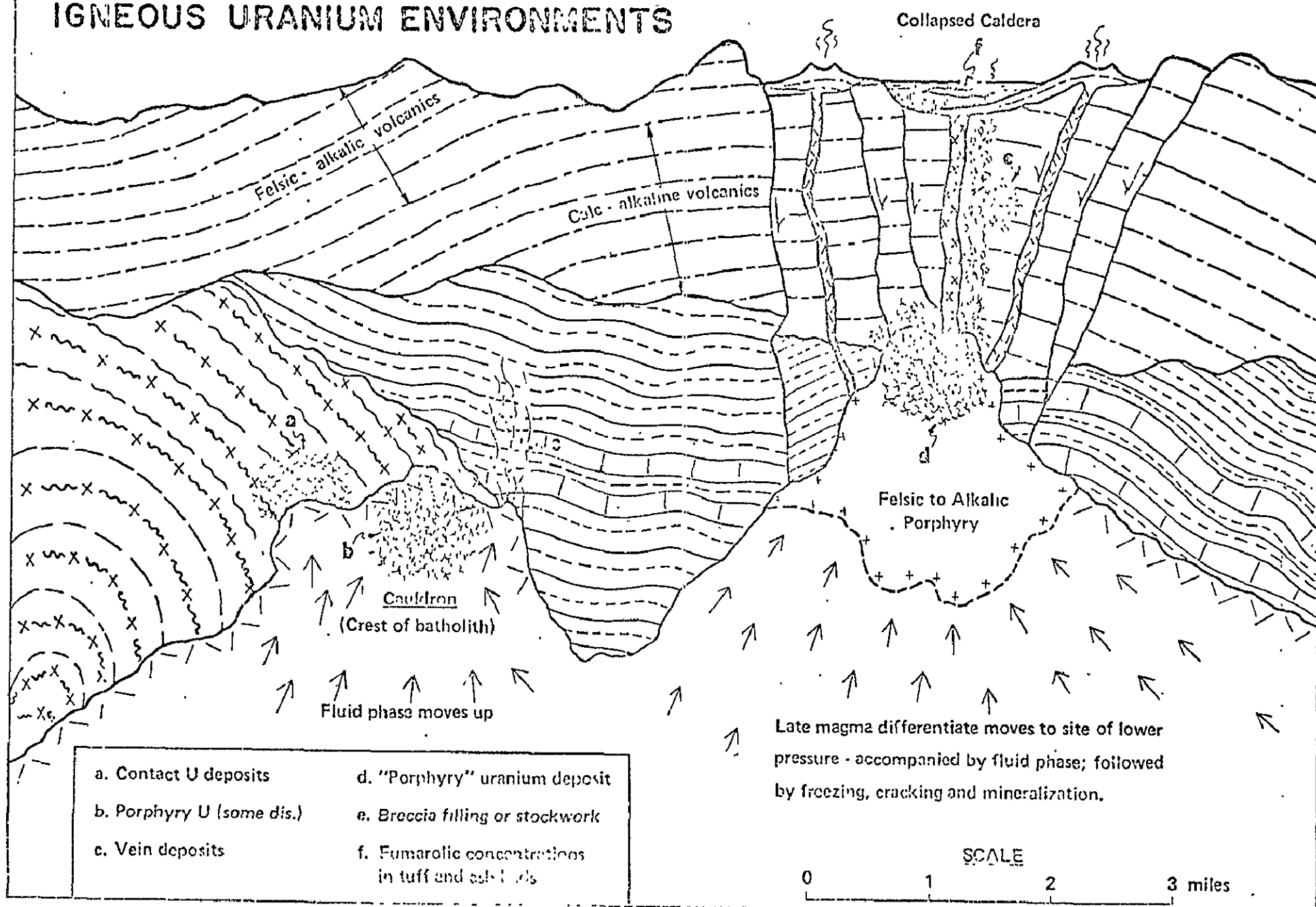
Low grade "porphyry" type uranium deposits have yet to be discovered, but they certainly are a possibility. Plate K illustrates two possible environments in which this type of deposit may occur. The first is the "cauldron", batholithic hood zone trap environment in which late magmatic uranium-bearing fluids and gases have accumulated. Upon crystallization of the final, potash rich magma, and subsequent cracking the uranium mineralization is visualized as having formed as joint and crack fillings and disseminations in concentrations ranging from 0.02 to 0.03% U_3O_8 . Concentrations of this order of magnitude are estimated to be economic at the projected \$25/lb for U_3O_8 . The second "caldera" environment represents a site where the roof of the batholith has been breached resulting in volcanism and subsequent caldera collapse. It is visualized that late magmatic differentiates then accumulated including a uranium-bearing fluid phase. If this late differentiate was trapped beneath the caldera neck in a cracked area a porphyry uranium deposit may have resulted. If the differentiate moved upward into the roots of the caldera as a series of multiple intrusives, uranium may have concentrated in breccias and stockworks near the surface. Or, if the fluid phase moved up into the caldera basin uranium may be concentrated in the ash, pyroclastics and lake sediments much as in the alkaline volcanic centers in central Italy.

Epigenetic uranium deposits also are found around the contacts of batholiths of felsic to alkalic composition (Plate K). Major uranium vein deposits also occur in the vicinity of intrusives of this compositional range in Africa, Canada, Eastern Europe and Colorado.

SEDIMENTARY EXHALATIVE DEPOSITS

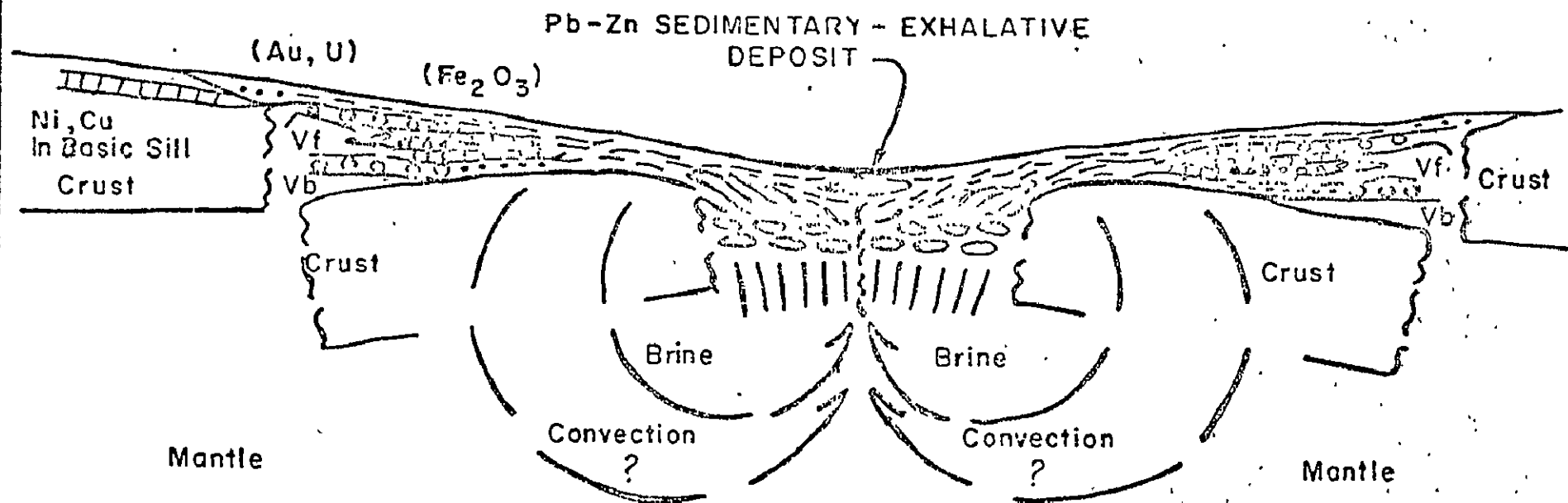
Sedimentary exhalative massive base metal sulfide deposits are closely related in genetic processes to the volcanogenic Archean and younger subduction zone types. They too formed from sea-floor exhalative, metal-rich brines (Plate L). However, they lack the thick volcanic succession that is so characteristic of the former and they occur in reduced fine-grained argillites or shales. They also lack Cu, being rich in Pb-Zn and Ag and are sometimes very large, up to 200 million tons. They are commonest in Proterozoic rocks rather than Archean ones, as for example the Sullivan deposit at Kimberley, British Columbia and Broken Hill in New South Wales. They

IGNEOUS URANIUM ENVIRONMENTS



ALL MAGMATISM CEASES,
FUMAROLIC BRINE EMISSION
IN CENTRAL RIFT

THICK, DEEPWATER
ARGILLITES FILL CENTRAL
TROUGH



LATE STAGE RIFT ENVIRONMENT

Vf Felsic Intrusives And Vol.-
Often Mineralized.

Vb Basalt - Intrusives And Vol.

Both Interbedded With Clastics
And Evaporites.

MAJOR SUBSIDENCE OF DETACHED
BLOCK COMPLETED

TECTONIC STABILIZATION

after Hutchinson

were formed in deep, probably rift-controlled trenches that were filled with thick turbidite type clastic sediment.

The Salton Sea system is similar except that convection of hot brines is effective in permeable silts and fine sands under a 3,000 foot cover of tight silts and shales. The thermal energy is supplied by buried obsidian domes within the Gulf of California - Salton Sea trench. Zinc, lead, copper sulfides are depositing at the base of the cover sediments in appreciable quantities from a brine system containing several hundred million dollars worth of total metals. The metals and the salines of the system are believed to have been derived from meteoric water leaching of sediments to the east with some magmatic addition (see Plate M and Table II).

CONNATE AND/OR METEORIC SYSTEMS

Connate and meteoric "hydrothermal" systems are believed to have been responsible for many of the base metal deposits in the Mississippi Valley, but again with some local addition of metals from buried, alkalic igneous intrusions. These intrusives are thought to have supplied thermal energy to start circulation of connate and meteoric waters which leached metals and salines largely from Precambrian rocks but in part from Paleozoics within or in the near vicinity of these mineral districts. These metal-bearing fluids in turn searched out favorable sites for deposition including karst zones, slumped sedimentary zones, leached and collapsed carbonate-rich horizons, reef fringes and permeable fault zones (Plate N).

The copper deposits at White Pine, Michigan, also may have been formed by connate-meteoric water transport of copper by metal-bearing salines. White and others point to the possibility that copper was leached from underlying copper-bearing basalts, transported through the Copper Harbor conglomerate and up into the base of the ore-bearing Nonesuch shale to form a "brine ridge" during the diagenesis of these shales. Native copper is found in the top of the Copper Harbor conglomerate and chalcocite, bornite, chalcopyrite and pyrite successively upward in the 50 foot high ore zone, in the Nonesuch shale. Remnants of highly concentrated brine are found in the ores (Plate O - O')

The chemical cell-roll front system, accepted by many as responsible for the uranium-vanadium deposits of the Colorado Plateau and the Wyoming clastic-filled river channels and basins, is another example of a meteoric system. According to this theory migrating oxidizing ground waters have leached and mobilized the uranium contained in the clastic granitic debris and it has deposited at or near the chemical cell interface with these advancing waters and the initial connate waters in the channel systems. Harshman and others point to Eh and pH as major controls along these roll fronts (Plate P). Biogenic contribution also has been significant with *Clostridium* and *Desulfovibrio* species active in the protore zone ahead of the advancing front and *Thiobacillus oxidans* on the oxidizing side of the cell front.

Major uranium mineralization also occurs in Proterozoic clastic filled basins of the Rand in southern Africa and in the Blind River region of Canada in association with placer gold deposits.

	SALTON SEA BRINE ¹	RED SEA BRINE (ATLANTIS II DEEP) ²
Temperatura (°C)	340 - extrapolated	56.5
Depth (ft)	5,540 - below surface i.e., "intrusive"	7,300 - below sea level i.e., "sea bottom"
pH	4.5 - (calculated)	5.9-6.5
Eh (mv)	?	very low; 310-350
Total Salinity (ppm)	240,000	258,000
Cl ⁻ (ppm)	163,500	156,000
Na ⁺ (ppm)	51,600	92,600
K ⁺ (ppm)	17,460	1,870
Na/K	3/1	55/1
Ca ²⁺ (ppm)	29,360	5,150
Mg ²⁺ (ppm)	40	764
Fe ²⁺ (ppm)	1,998	60
Mn ²⁺ (ppm)	1,418	70
Ag (ppm)	2.1	.003-.3
Cu (ppm)	4.4	.26
Pb (ppm)	85.6	.63
Zn (ppm)	528	5.4
Ba (ppm)	225	?
As	12	n.d.
Sb	.4	tr.
SO ₄ ⁻ (ppm)	7.7	840
S ⁻ as H ₂ S (ppm)	16	nil
S ⁻ as HS ⁻ (ppm)	14	nil
SiO ₂ (ppm)	400	23

Precipitates from brines

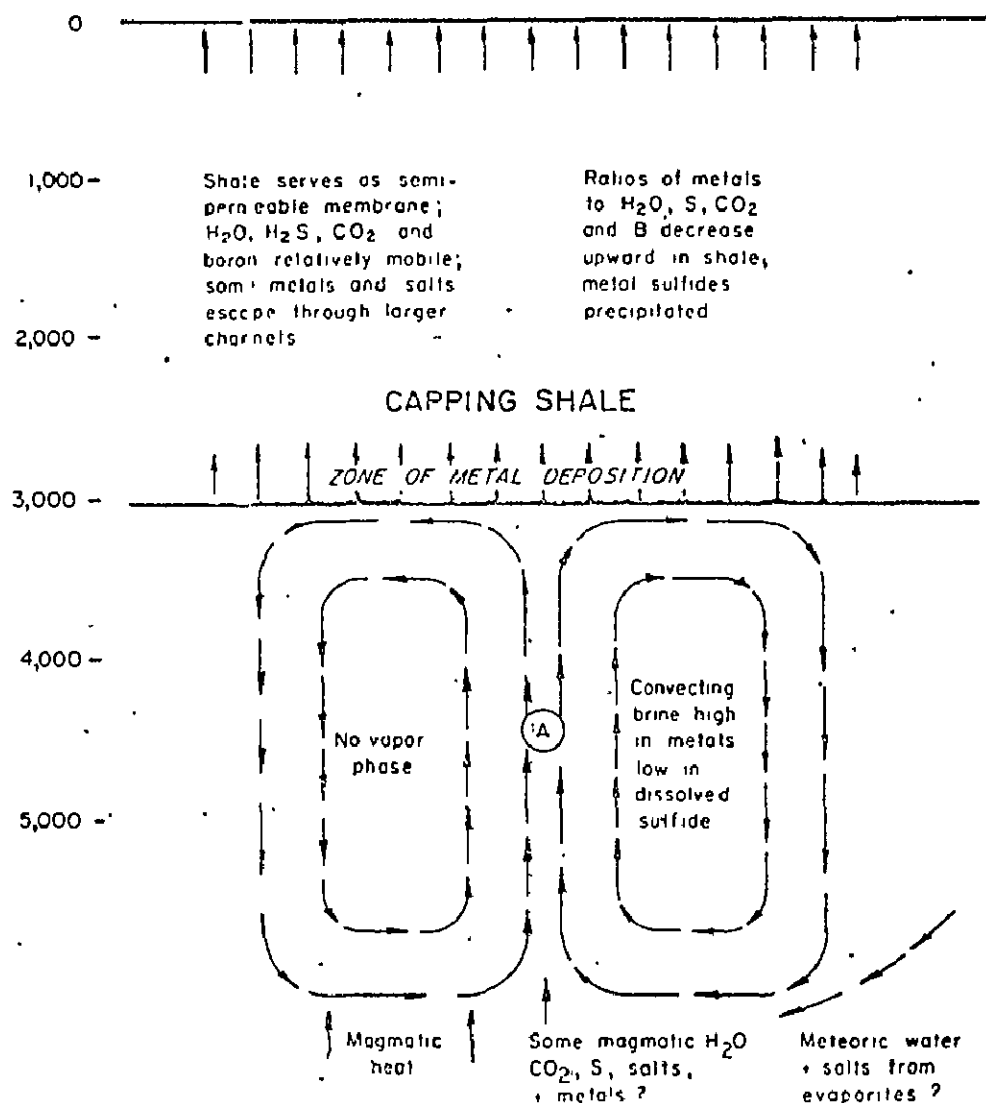
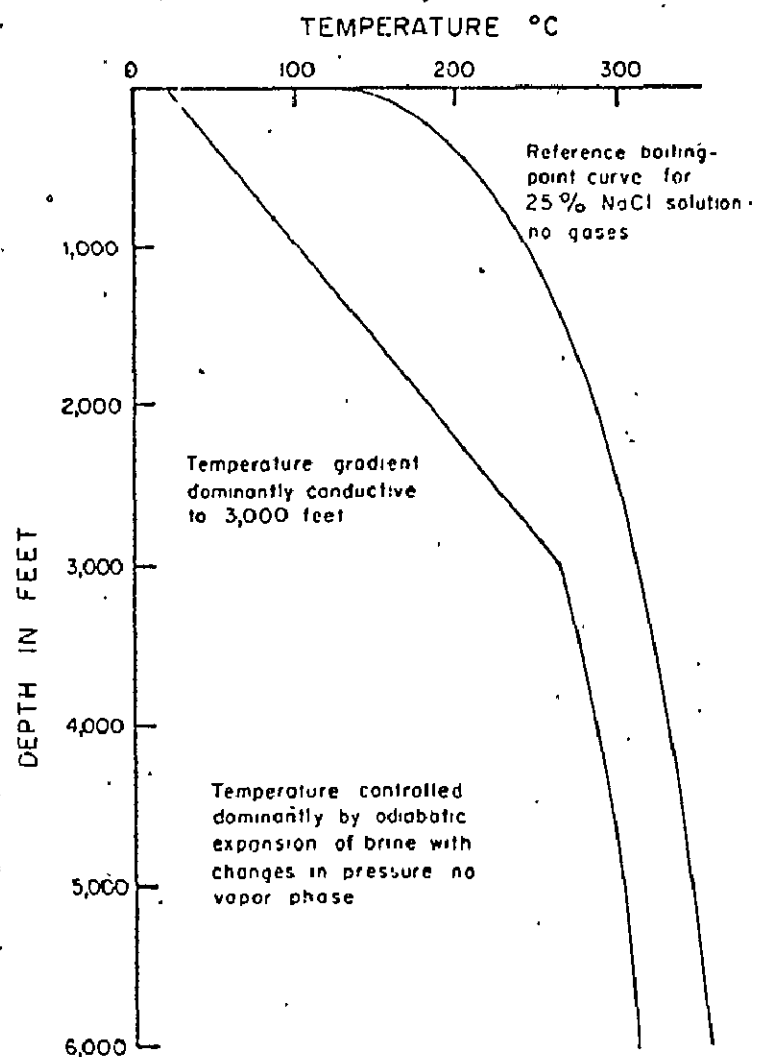
a) location	higher in drill pipe or at surface effluent	at sea floor site
b) general nature and composition	opalline silica amorphous Ag Ag-Cu sulphides Cu sulphides Cu-Fe sulphides Cu-Sb-As sulphides	- complex with various facies, all precipitates amorphous; - sulphide facies has silica, Fe, Zn, and Cu sulphides; - oxide facies has silica Fe, Mn oxides.

1) White, D. E., 1968.

2) Degens, E.T., and Ross, D.A., 1969

COMPARISON OF METAL-BEARING CHLORIDE BRINES

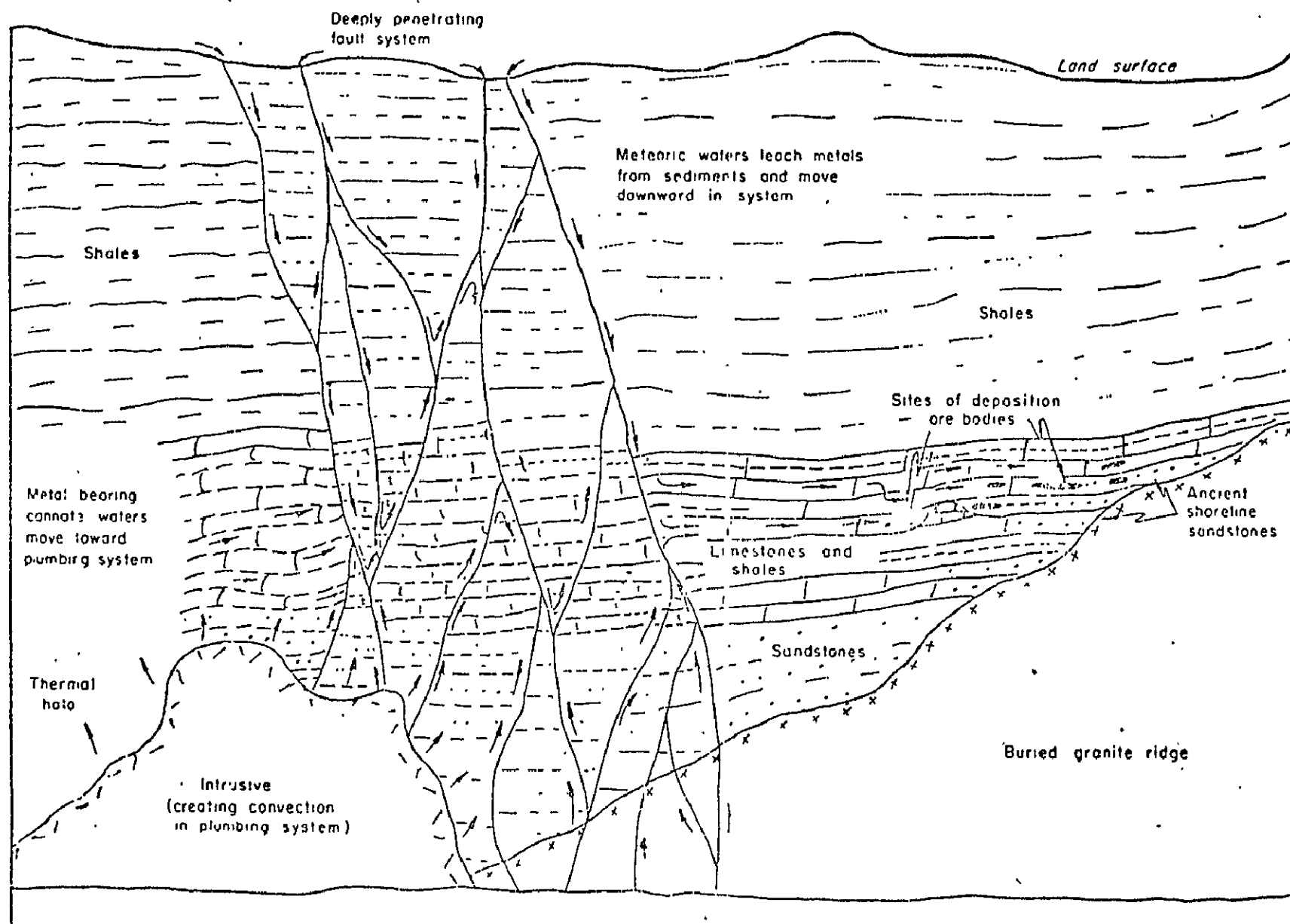
TABLE II.

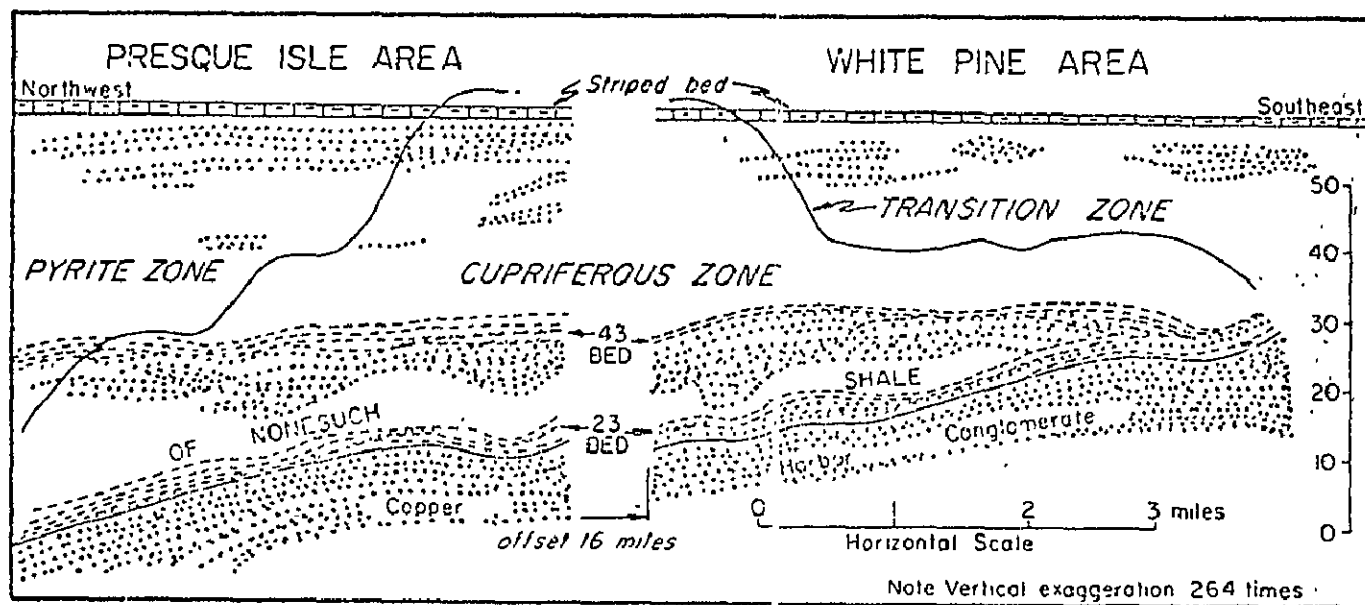


Model for Salton Sea geothermal system, assuming absence of a vapor phase, but selective escape of H_2O , H_2S , and B by membrane filtration through the capping shale.

(after White)

CONNATE - METEORIC WATER SYSTEM

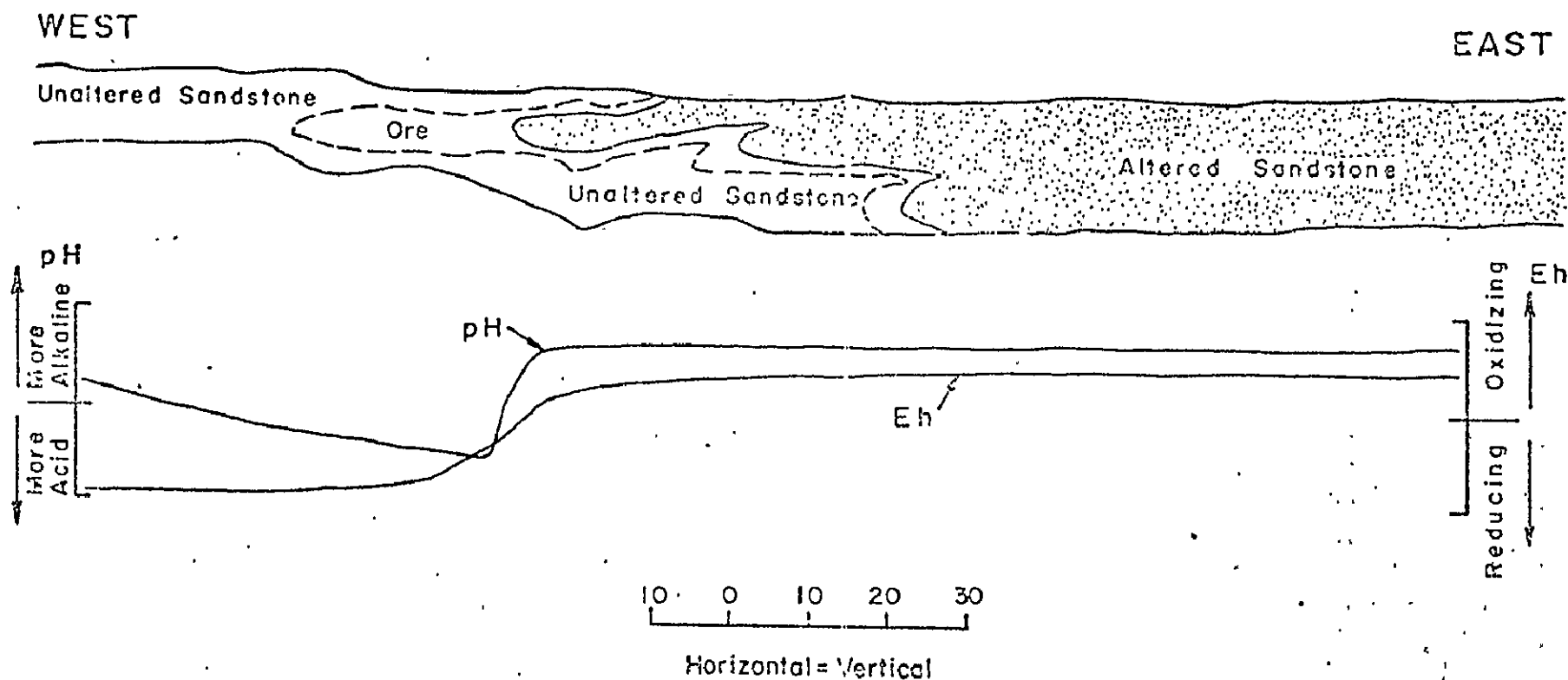




RELATIONS OF THE CUPRIFEROUS AND PYRITE ZONES TO
THE BASAL PART OF THE NONESUCH SHALE, NORTHERN MICHIGAN

(after White)

URANIUM ROLL FRONT ENVIRONMENT WYOMING BASINS AND COLORADO PLATEAU



after Harshman

LAGOONAL SYNGENETIC ENVIRONMENT

Many Australian and South African geologists favor lagoonal or marine embayment environment to explain the formation of the very extensive and rich copper, lead, and zinc deposits of the African copper belt, Mt. Isa, and Broken Hills (Plates Q and R). Most agree that lagoonal or marine fringe waters must have been enriched in metals from supplemental sources for the volume of metals present in very narrow sedimentary bands is far greater than the metals available from normal lagoonal and sea waters within the time span of deposition. Supplemental sources are under-water volcanic fumaroles and hot springs, transported detrital particles, suspended mineral and metal ions, or metal-bearing brines moving beneath the mineralized horizons. It is proposed that these brines carry metals as chloride complexes and move up into the diagenetic muds and oozes during consolidation similar to that proposed for White Pine, Michigan. Other specialists propose instead that later brine ingress, long after consolidation, is responsible. The brines in this instance were elevated in temperature and were moved about as hot fluids deep in a sedimentary basin because of a change in the hydrostatic balance in the basin system or by intrusive thermal centers as in the case of the Mississippi Valley environment. Both appear to be possible at Mt. Isa and the African Copper Belt, although evidence is incomplete. The Sabka process described by Renfro may have been the controlling mechanism for some deposits of this type.

The best example of lagoonal or shallow marine syngenetic ore accumulation is that of the iron deposits of the Great Lakes region of the United States and the Labrador trough of eastern Canada. They formed in shallow basins under conditions ranging from strongly reducing to oxidizing depending on the depth and distance from the shore line (Plate S).

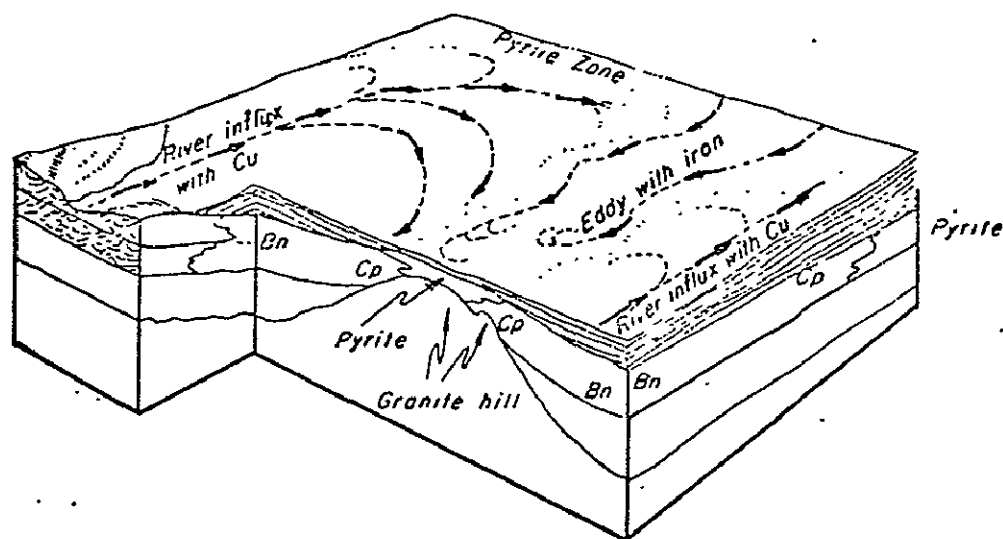
Iron sulfides form under reducing conditions, carbonates and silicates under transitional conditions and the oxides close to the shoreline where the waters are well oxygenated. The source of the iron is believed to have been from iron-bearing rocks in areas of low lying topography in a tropical belt undergoing deep chemical weathering. However, rufaceous beds occur in the host sediments in the Central Swedish Iron Fields. There, volcanic fumaroles may have been effective on land or beneath the basin to enrich the waters in iron.

Coal also has formed in saline lagoonal fringes and flooded swamps along the low lying coast of ancient shallow swamps where clastic input was minimal.

MARINE SYNGENETIC ENVIRONMENT

Phosphate rock precipitation of the Phosphoria formation of southeastern Idaho and southwestern Wyoming and the great phosphate zone trending across North Africa and the Middle East represents marine syngenetic genesis. Upwelling cold waters containing phosphorous, nitrogen, carbon dioxide and silica have deposited phosphate rock, chert, and carbonates progressively upward along the shoreline profile. Salines often are found in adjacent, interior evaporite basins (Plate T).

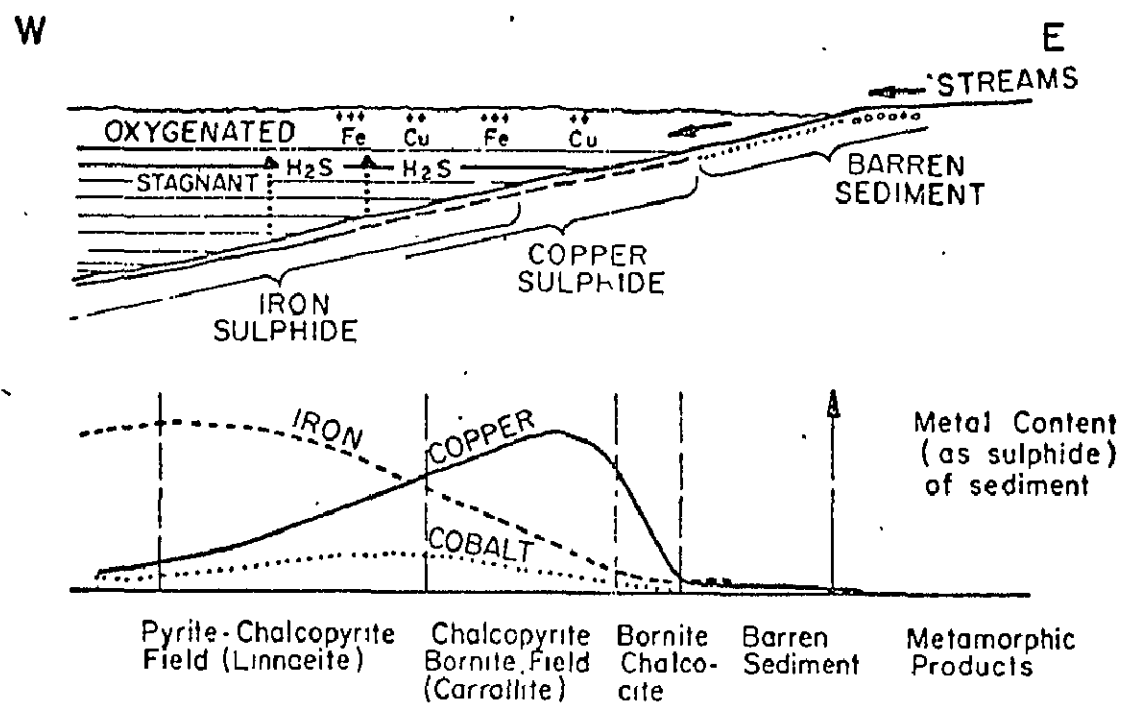
PROPOSED SYNGÉNÉTIC ENVIRONMENT
FOR AFRICAN COPPER BELT ORES

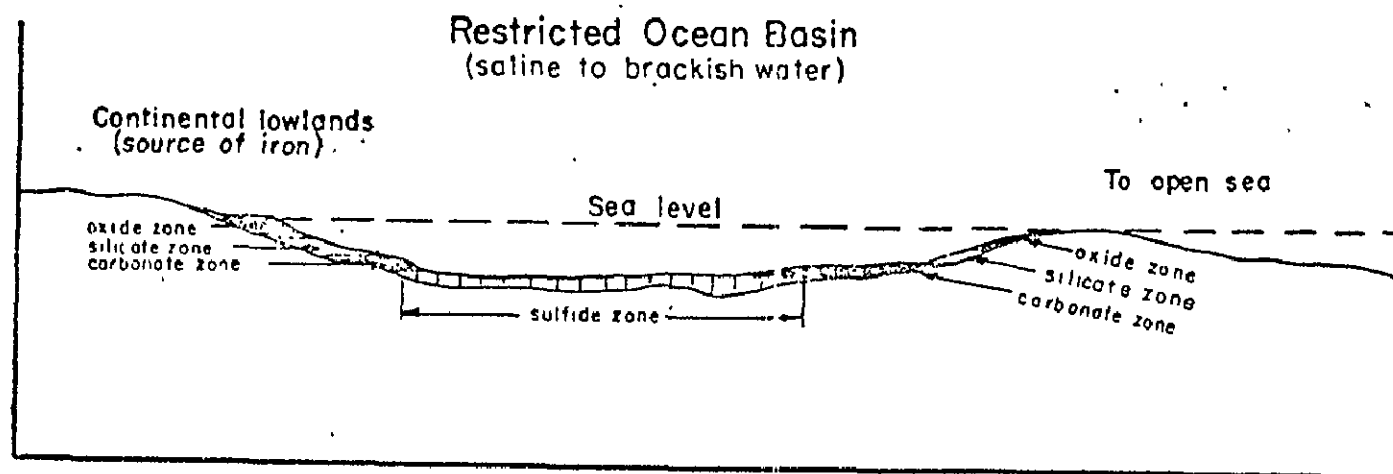


Not to scale

After: Mendelsohn

ZONAL DISTRIBUTION OF COPPER ORES ALONG THE SHORELINE PROFILE

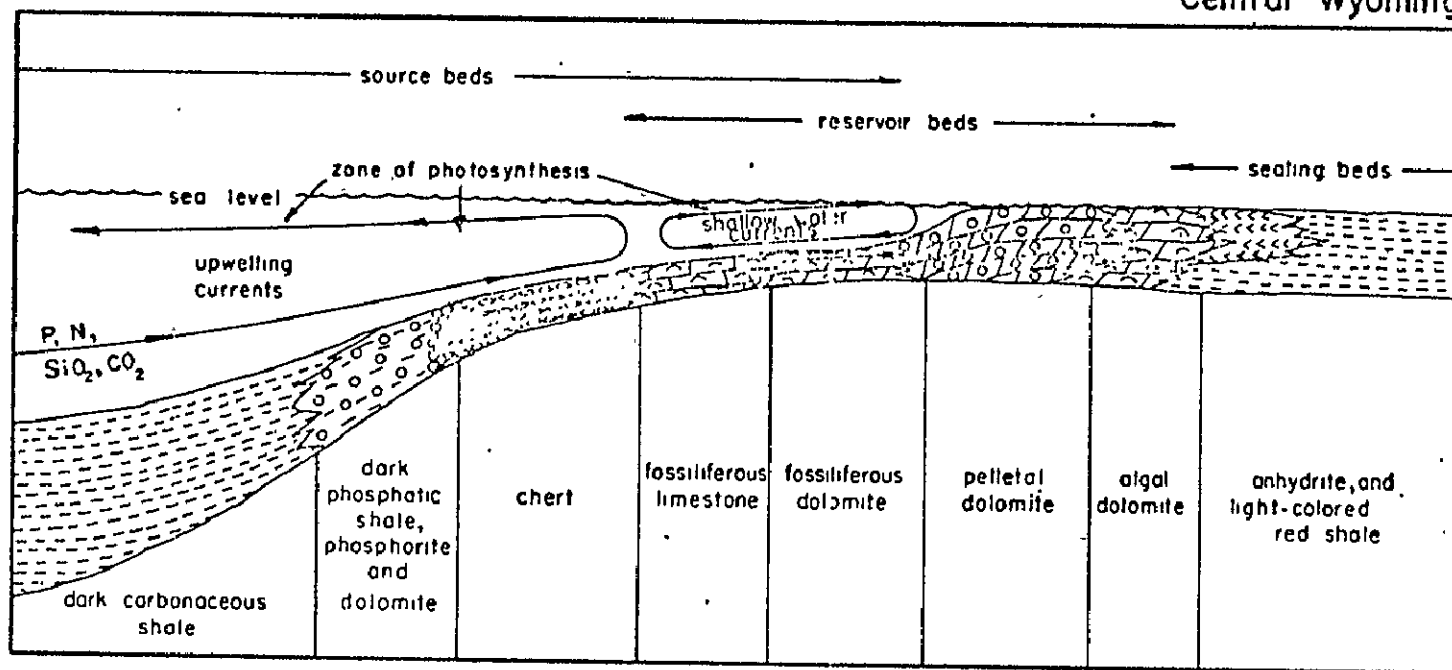




ZONAL DISTRIBUTION OF IRON MINERALS
IN A SHALLOW SEA-LAGOONAL ENVIRONMENT

W.
Southeast Idaho

E.
Central Wyoming



Idealized sedimentation in Phosphoria sea.

(after Sheldon)

The conditions under which phosphate rock forms in this environment are rather exacting. Deposition occurs along cratonic fringes where offshore winds or ocean currents drive the surface waters seaward resulting in the upwelling of deep, enriched, cold waters. The adjacent landmass must be warm and arid and shed no clastics into the depositional zone, and there must be an extended period of tectonic stability. Deposition of phosphate rock, chert and carbonates along the shoreline profile is greatly enhanced by the very rapid growth of organic life in the zone of photosynthesis. The remains of these micro and macro-organisms, rich in phosphate, silica and calcium carbonate drift down to the shoreline profile and enrich the chemically deposited materials in each zone. Profile chemistry dictates phosphate rock stability under intermediate Eh and pH conditions. Chert and carbonates are stable under higher Eh and pH conditions. Phosphate rock forms in a belt parallel to the shoreline. Chert and carbonate form in belts higher on the shoreline profile.

Important phosphate deposits have formed in the supratidal zone in northern Australia during the Cambrian probably as a reworking of shallow marine pelletal phosphorite of the Phosphoria type.

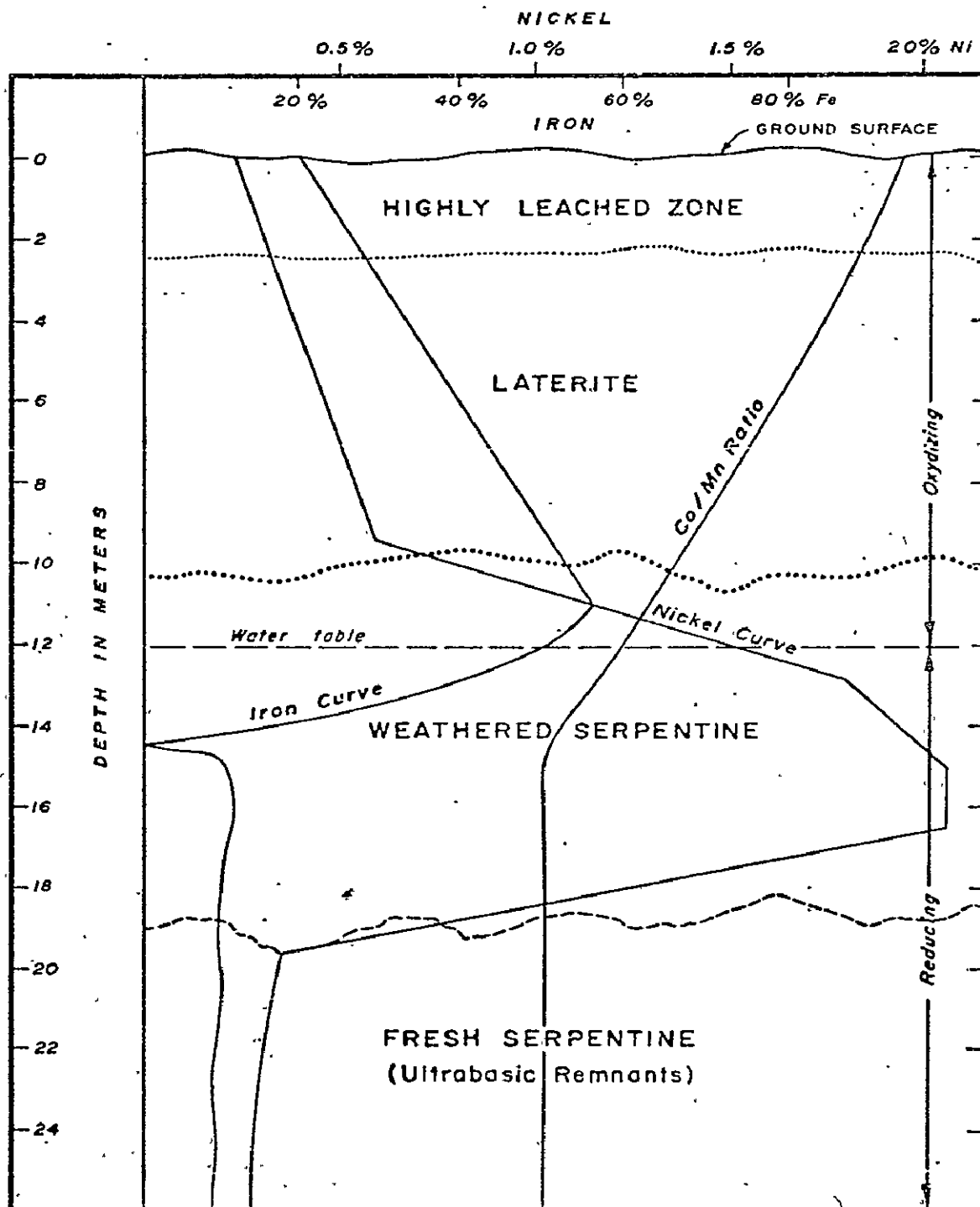
Major phosphate deposition developed in the river flood plain-estuary environment during the Pliocene in Florida. Phosphorite formed in river channels in this flood plain-estuarine transition zone as a result of phosphorous leached from the Miocene phosphatic Hawthorne limestone in the headwaters of the drainage area.

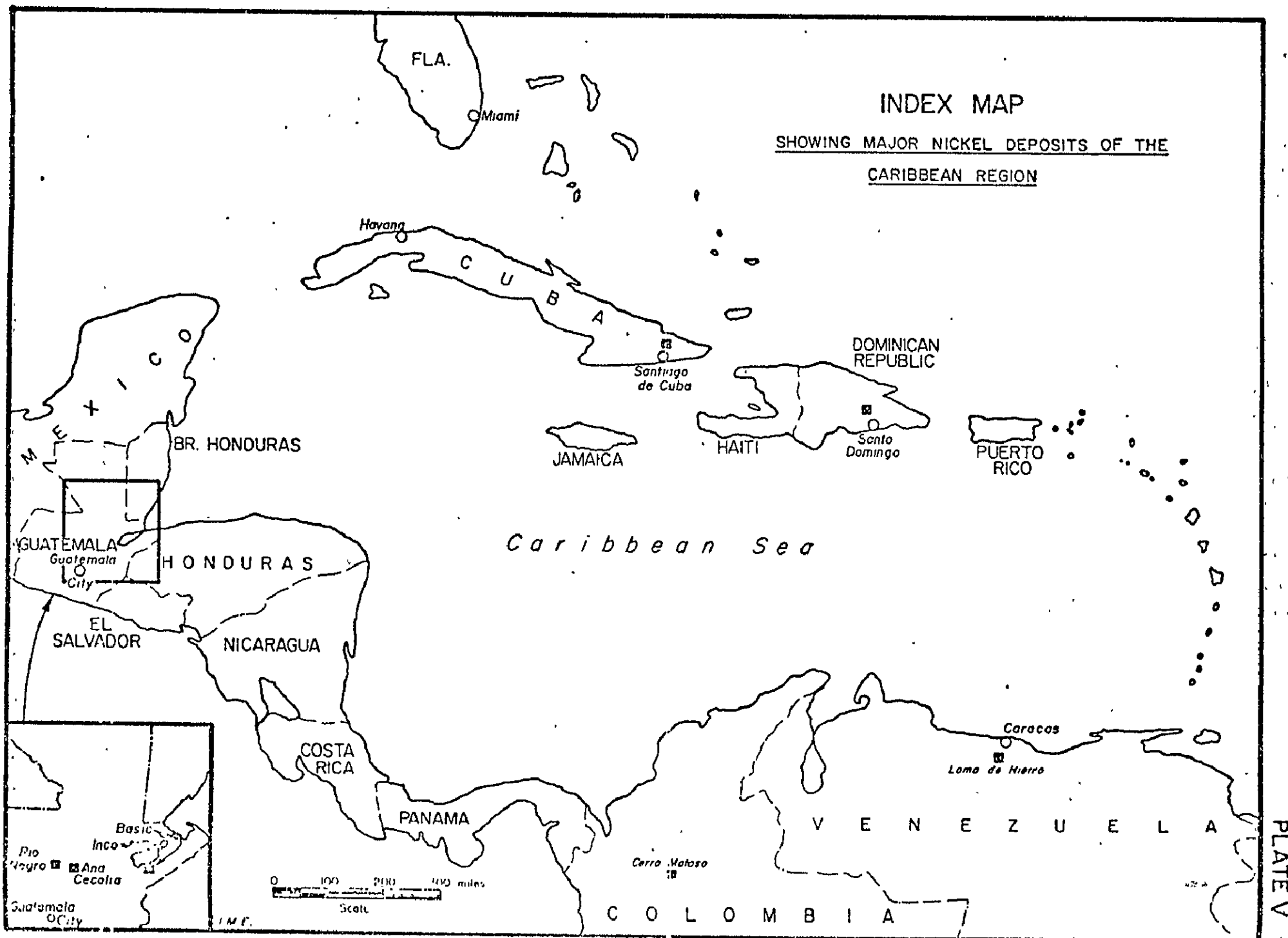
CHEMICAL AND MECHANICAL WEATHERING ENVIRONMENTS

Lateritic nickel and bauxite are two prime examples of mineral deposits resulting from extreme chemical leaching under tropical climatic conditions. Magnesium, potassium, sodium, calcium and silica are mobilized by deep chemical weathering to leave a highly ferruginous and/or aluminous cap. Nickel is upgraded by removal of ions in the lateritic (oxidized) A and B soil zones, and enriched at or below the water table by nickel transported as a soluble bicarbonate to the C soil zone and to fractures in the bedrock ultra basic rocks (Plate U). Important lateritic nickel deposits occur around the Caribbean tectonic belt from the Cerro Matoso deposit in Colombia to the Loma de Hierro in Venezuela, the Falkenbridge in Santo Domingo, Nicaro and Morro Bay in Cuba to the Lake Izabal deposits of International Nickel in Guatemala. Bauxite formation is similar to that of lateritic nickel. It develops, directly under alkaline conditions, in the aluminous, weathered cap and as a result of desilication of clays as the water table is lowered.

Mechanically weathered, durable minerals and metals are concentrated by streams and wave action. Gold placers, monazite placers, and tin placers have been concentrated in river channels, and in some localities by wave action, where as iron-titanium and chromium-rich black sands have formed as a result of concentration by strong wave action. A 300,000 million ton. titaniferous black sand deposit has formed on the south coast of Java. It is 23 km long, 1 1/2 km wide, and 8 meters deep. A pelletizing plant soon will be constructed at this site by an American-Australian group.

APPROXIMATE METAL DISTRIBUTION CURVES IN THE Lake Izabal Nickel Deposits GUATEMALA





FORMULATING AN EXPLORATION PROGRAM

OBJETIVE OF A COMPANY OR PRIVATE SYNDICATE

A mineral exploration program is patterned around specific objectives. Most large foreign corporations and consortiums which search for metals and minerals do so for the purpose of supplying low cost, in-house supplies of one or a limited number of raw materials for upgrading, refining, fabricating and marketing of final products. Often the cost of discovery and exploitation is a small part of the total cost as profits are related to the final products, not directly to metal or mineral exploitation. Other companies produce only metals and minerals, a few sell just concentrates and usually only small mines sell raw ore to custom mills. A private syndicate on the other hand, may not plan to exploit an ore deposit. Instead they may sell out to a large company or become a partner with a carried interest. Others may complete only early and mid-level exploration in order to locate promising targets and then sell out. National mining companies in developing countries usually go no further; they rely on well financed foreign joint venture partners with expertise to discover, outline, develop and mine the orebodies.

The objectives of large foreign company exploration programs usually is to find ore reserves sufficient for 10 to 30 or more years production. Management is satisfied with a smaller orebody with a shorter productive life if the product is high priced, such as uranium, gold, and silver. Most private groups, because of limited budgets, must search for the smaller, high grade orebodies unless they wish to sell out at the target stage for a modest return. They do not have the resources to go further.

SELECTION OF AN EXPLORATION AREA

The U.S. investor, whether a large company or a smaller group, must choose between domestic and foreign exploration. The intensity of the mineral exploration effort during the past twenty years in the United States has been high. Certainly, most of the more easily discovered, near surface deposits have been located, drilled and are under development or are being mined. New, major discoveries in the United States will be deeper and much more difficult and expensive to find.

Temporarily, the U.S. mineral industry has received a "bonus" as most metal prices have risen faster than costs because of growing shortages of many metals and mineral products. Whether metal and mineral prices in the United States will continue to rise appreciably ahead of costs is debateable. For this reason many companies are beginning or are intensifying overseas exploration efforts in countries where political and economic projections appear favorable. They anticipate finding new, large tonnage, low cost deposits. The Philippines, Indonesia, Brazil and Colombia have strong discovery potential and are reasonably stable. Australia and British Colombia, and the Latin American countries along the central part of the Andean belt also offer excellent promise. At present the political backdrop of these countries is unfavorable, but may improve.

ACCEPTABLE DEGREE OF RISK IN MINERAL EXPLORATION

The degree of risk allowed by management dictates the type of program which the exploration manager can formulate and execute. Some companies wish to acquire proved or probable ore reserves in favorable political areas, thus keeping the risk at a minimum. Others are willing to carry out exploration in remote areas of the world where little geologic information is available and politics is uncertain.

Discovery potential, and thus *geologic* risk, can be clarified for management by charts utilizing the degree of certainty against the feasibility of economic recovery as shown on Plate W. The framework of this chart was developed initially by McKelvey. The zones indicated by numbers across the base reflect the amount of knowledge available. In Zone 1 little is known except for regional geologic data such as an ultrabasic zone favorable for lateritic nickel deposits in a tropical region of the world. In Zone 2 the overall knowledge is somewhat more advanced.

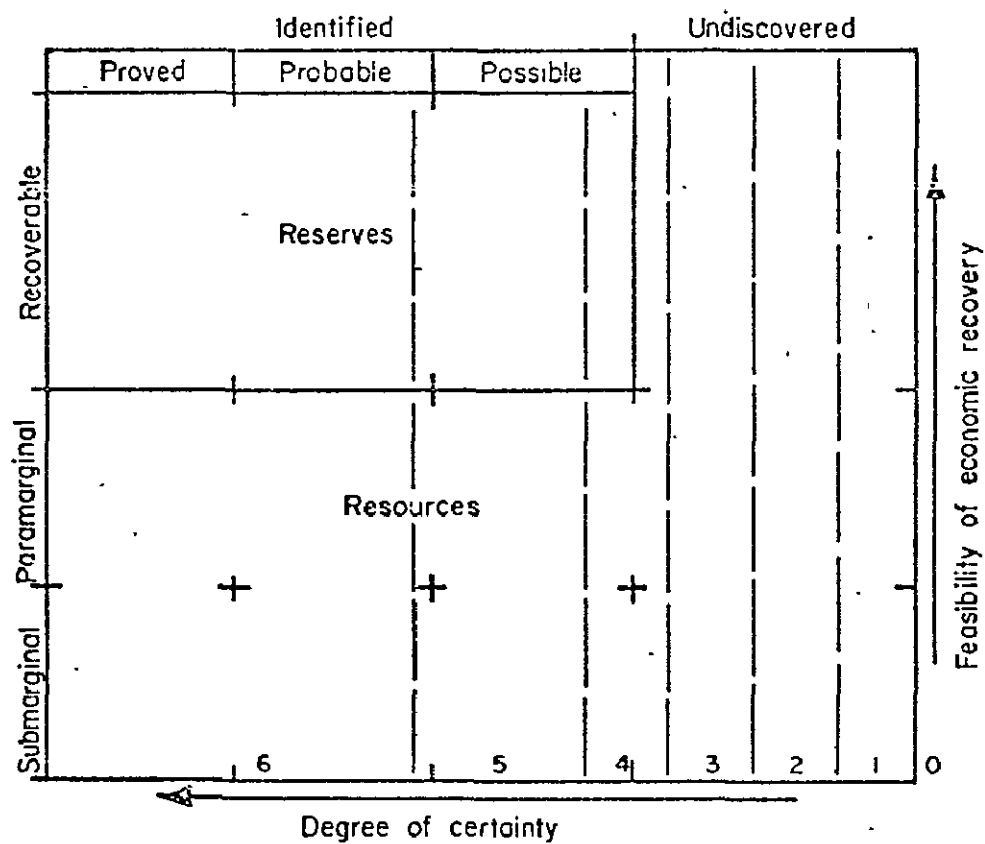
Recently, discoveries were made in such relatively unknown regions both in Indonesia and in Guatemala. Seven years ago an exploration program was launched in central and western Guatemala to search for lateritic nickel deposits. It started with a broad, regional approach with initial knowledge approximating Zone 2 on the chart. It resulted in the discovery of one orebody and one submarginal deposit. Exploration progression is shown on Plate X as "x". Program "y" involved a gold prospect which was brought up to the paramarginal level, but both grade and tonnage were insufficient. Program "z" involving mercury did not progress further than the mineralized target level and was dropped. In some instances a small, high grade mine can be expanded into a large operation by an analysis of the total low grade potential as at Questa, New Mexico, where a 50 ton per day 5% MoS_2 operation had existed since 1923. In the mid-1950's a major exploration program was started which resulted in the present 15,000 ton per day open pit operation with an average ore grade of about 0.22 % MoS_2 . Plate Y illustrates how initial exploration expanded the ore potential, and further exploration and development work established a large ore reserve of low grade material.

APPRAISAL OF THE MINERAL DISCOVERY POTENTIAL

The mineral discovery potential of a region can be out-lined in general terms by utilizing the chart (Plate W) and assessing the key phases of the exploration program on the following basis:

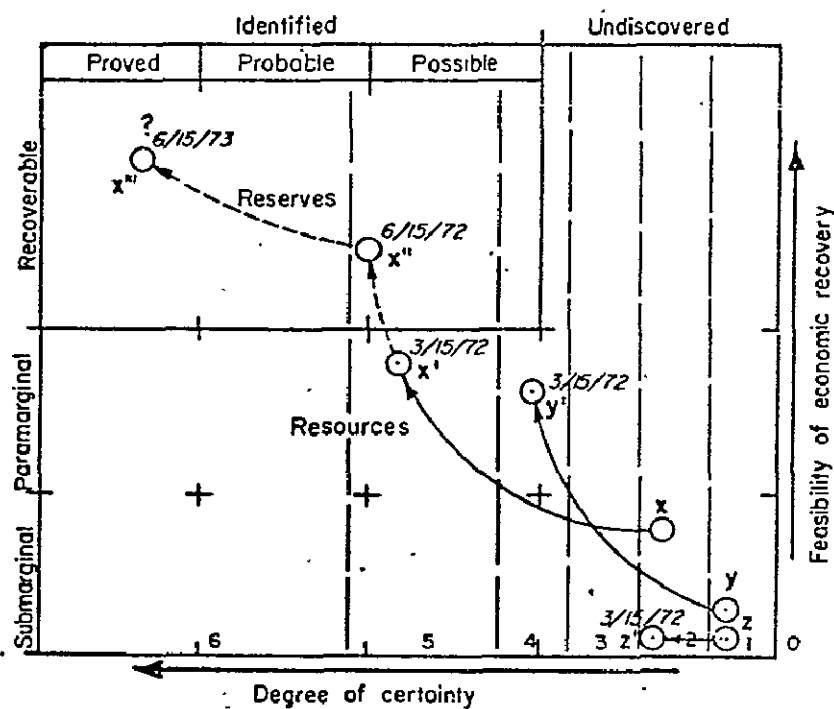
- Zone 0. The right hand boundary can be considered as zero degree of certainty.
- Zone 1. The identification of target areas by reconnaissance investigations.
- Zone 3. Identification of targets utilizing semidetalled geologic mapping, geophysical, geochemical and other data-gathering techniques.
- Zone 4. Probe drilling of targets to verify mineralization in plan and the third dimension supported by Zone 3 techniques.

CLASSIFICATION CHART FOR MINERAL RESOURCES AND RESERVES



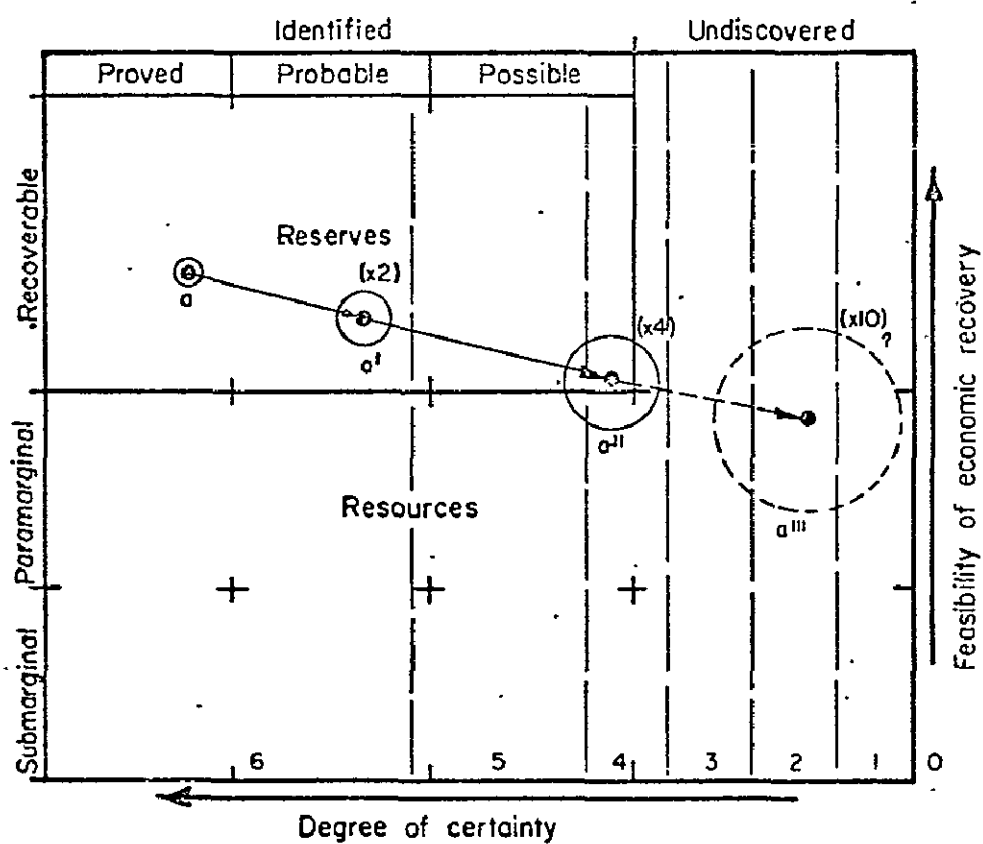
(after McKelvey)

CLASSIFICATION CHART FOR MINERAL RESOURCES AND RESERVES



(after McVee)

CLASSIFICATION CHART FOR MINERAL RESOURCES AND RESERVES



(after McKelvey)

Zone 5. Exploration drilling. Systematic, third dimension. evaluation of the mineralized body, also supported by geophysics.

Zone 6. Finally, offset drilling and underground (mine) penetration is completed to establish the tonnage and grade and specific character of the proved orebody.

ESTIMATION OF RESOURCES

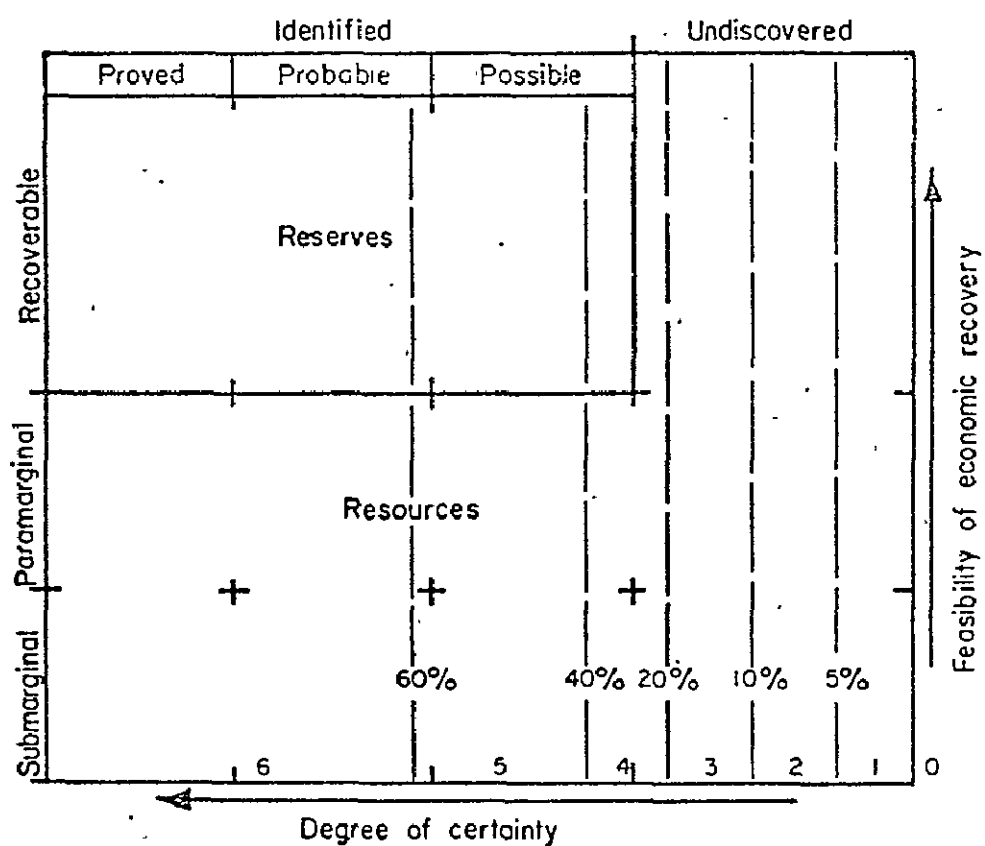
Methods of calculating proved, probable and possible *ore reserves* have long been established. How should *mineral resources* be categorized? We can, with some assurance, predict "discovery potential" outward from or at depth beneath a drilled out portion of a porphyry copper orebody because of geologic knowledge and statistical data which are available. Predictions of the discovery potential also are possible when projecting a coal seam from an operating mine on one side of a high topographic ridge to an operating mine on the other side some kilometers distant, or the probability of discovery of a uranium orebody in an unexplored block of ground containing an ancient river channel in which sizeable uranium orebodies have been discovered and mined in the channel on both sides of the block. Sufficient data are available in all three cases to apply statistics, and a reasonably firm prediction as to the discovery potential can be obtained.

When one moves further out into the unknown by moving laterally on the Degree of Certainty base of the chart, the predictions of discovery become very tenuous. However, utilizing a considerable degree of caution, we can estimate percentages for the discovery potential for the various zones. For example, 5% might be assigned to Zone 1, 10% to Zone 2, and 20% to Zone 3 (Plate Z). It becomes apparent immediately that 5% may be high for the discovery potential in Zone 1, where all that is known is that the overall environment is reasonably favorable for mineral concentration. The great majority of these environments are essentially barren. Only a few contain mineralized bodies and only a few of these are orebodies. For this reason the 5% discovery potential factor should be applied only to carefully selected environments of Zone 1 about which there is considerable backdrop geologic knowledge.

Can we assign 10% probability to a target in Zone 2? This depends upon the amount and reliability of geologic data pertaining to the target. For example, if the presence of a porphyry intrusive body has been established, are any of the following favorable criteria indicated?

1. Strong hydrothermal alteration within and halo to the intrusive?
2. Promising surface geochemical anomaly of metals and trace elements indicating the presence of copper and molybdenum mineralization near the surface.
3. The probability of semi-trap conditions to localize the widespread mineralization rather than its loss through an open plumbing system?
4. Development of extreme pre-mineral cracking to open the porphyry, the hood zone and flanks to low-grade mineralizing fluids.

CLASSIFICATION CHART FOR MINERAL RESOURCES AND RESERVES



(after McKelvey)

5. Geophysical data indicating the presence of wide-spread sulfide mineralization in the subsurface?
6. Evidence for the presence of extensive and wide-spread pyrite to enhance copper leaching in the zone of weathering and thus the possibility of supergene enrichment at the water tables?

If half of these favorable criteria are present, the target should be given a 10 % probability rating in Zone 2. Not all will be apparent, for Zone 2 represents the identification of targets within target areas prior to any intensive study.

If all of these criteria become apparent during the investigations included in Zone 3, a 20% discovery probability would seem reasonable.

Once probe drilling in Zone 4 has established strong mineralization of ore grade in the third dimension, the probability of discovery of a sizeable mineralized body would rise rapidly to, say 40%.

Systematic drilling in Zone 5, would in turn increase the probability of discovery of an orebody to perhaps 60% and, if the values are high, the favorability of economic recovery would increase in relative proportion to the assays and tonnage.

EXECUTION OF THE EXPLORATION PROGRAM

Most exploration programs are phased starting in any one of the zones of certainty described above depending upon the amount and reliability of the data available. The first step is to familiarize the investor (management or private investors) with the program, its objectives and initial risk, timing and cost. At the end of each phase progress reports are submitted, reviewed by the investor, and if approved the next phase is executed. In this way the exploration manager and/or consultant clearly states his findings at the end of each stage, makes his recommendations and secures approval of the program and budget for the next phase. Thus misunderstandings are minimized between the exploration manager and the investor.

The expertise represented by the staff of the exploration team will change from early reconnaissance through exploration, development and finally exploitation of the orebody. Usually three or four top level professionals will execute the program through to production in order to give the program continuity. Some programs are supported largely by contractors who complete early airborne geophysics and petrogeology together with applicable remote sensing techniques. Often much of the ground geophysics, and geochemical prospecting and trace element studies also are completed by contracting teams, as well as laboratory backup work. Bulldozing and drilling generally are contracted. But the critical geologic mapping, compilation, and correlation should be carried out by inhouse, experienced staff, and the final interpretation and evaluation by senior staff and closely associated consultants. The conclusions and recommendations of the progress reports and the final reports are of course fully evaluated and decisions reached by management or the investor.

THE PAPAGO EXPLORATION PROGRAM

Recently, one of the large U.S. mining companies successfully completed a phased exploration program within the Papago Indian Reservation in southwestern Arizona with the discovery of a new, porphyry copper orebody as its objective.

Their first step was to study the overall features of the entire porphyry copper mineral province of the western United States. It extends from Oregon and Idaho on the north, to the State of Sinaloa in Mexico on the south and as far east as Texas on the southeast. This province is believed to represent a "stretched" portion of the North American craton, caused by the migration of the East Pacific Rise eastward under the edge of the continent.

Several factors caused this company to concentrate their efforts in southwestern Arizona rather than in Nevada, New Mexico or Sonora. Among these is that Arizona is located within an area of strong tectonic intersection. Fault systems converge into the area from southern California on the west, from Nevada on the northwest, from the western fringe of the Colorado Plateau in Utah on the north, and from the southern fringe of the Plateau in New Mexico on the northeast. There are numerous igneous intrusions in the area including a large number of mineralized porphyry stocks and many large open pit porphyry copper mines. The entire southern part of the State can be considered a target area.

The Company selected the Papago Indian Reservation as a specific target area. Several large open pit mines are located around the fringes. It had not been explored thoroughly because of unfavorable mineral lease terms. These were being relaxed to a workable level.

Their program consisted first of a careful study of all aspects of the geology of southwestern Arizona and second of a closer view of the geology of the Reservation including Precambrian basement, the Paleozoic and Mesozoic sedimentary and volcanic stratigraphy, the sequential igneous intrusives, and the structural fabric, all of which were related to known porphyry copper deposits in the near vicinity.

Target areas then were selected in which a combination of favorable factors were present. All but one were eliminated. This was studied in semi-detail and detail by all applicable techniques and not only was drilled to outline a large body of porphyry copper ore, but also was penetrated by a shaft and drifts to evaluate detailed aspects of the orebody and to secure a bulk sample for metallurgical testing. The entire orebody was covered by a few feet to 200 feet of pediment gravels. It would be mined today except for insufficient smelter capacity in Arizona to treat the concentrates. It has been shelved temporarily.

Although budgets for this exploration program and a preliminary cost analysis are not available for this specific program, data from a very similar program are presented below:

OUTLINE FOR EXPLORATION PROGRAM AND ACCOMPANYING BUDGET

Phase A - Regional Evaluation.- A review of the regional tectonic framework, location and trends of igneous and volcanic activity and distribution of mineral districts and centers of mineralization. Field analysis of known deposits. Selection of the Papago Indian Reservation as a target area resulted. Two months at an estimated expenditure of \$ 25,000.

Phase B - Selection and Preliminary Evaluation of Individual Targets.- Five areas were selected, each with favorable tectonic, igneous, alteration or mineralization features. Four were shelved; one was recommended for semidetailed investigations. Three months - approximate expenditure - \$ 100,000.

Phase C - Geologic Evaluation of Prime Target Area.- Semidetailed geologic, geophysical investigations identified a widespread area of dispersed sulfides covered by pediment gravels. Detailed induced polarization pin pointed areas of concentration and probe drilling established between four and eigh hundred feet of promising mineralization beneath the gravels over an area of 1,500 feet by 3,200 feet. Mineralization occurred in intrusive porphyries, adjacent Precambrian schists and silicated sediments. Twelve months - approximate expenditure - \$ 280,000.

This target subsequently was drilled out resulting in the discovery of a large, low grade porphyry copper deposit. A preliminary economic evaluation was prepared. It has been modified to the extent of illustrating the cost and profit projections on the basis of a change in grade and 100,000,000 tns reserve. It is shown as follows:

1. Ore reserve: 100,000,000 SDT @ 0.50 percent copper
2. Stripping ratio: 2.0 W : 1.0 ore
3. Copper sales: 60 ¢ per pound
4. Production rate: 20,000 tons per day, 7,140,000 tons per year (357d).

5. Operating costs per ton:

Mining	3.0 x 30 ¢	= \$ 0.90
Milling		= 0.90
A & G		= 0.30
F, S & R	\$ 0.11 x 8.75 pounds	= 0.96
Total Operating		= 3.06

6. Extraction and recovery: 87.5 percent or 8.75 lbs per ton
7. Pounds recovered per year: 8.75 x 7,140,000 = 62,475,000
8. NSR per year: 60 ¢ - 11 ¢ = 49 ¢; \$ 0.49 x 62,475,000
= \$ 30,612,750

9. Capital cost: \$ 4000 per ton day = \$ 80,000,000
10. Depreciation: Capital cost $\div$ total recoverable pounds
 $\$ 80 \text{ MM} \div 8.75 \times 100,000,000 = 9.14 \text{ ¢ per lb.}$

	Copper Sales Price per Pound
	<u>60 ¢</u>
Metal sales per ton	\$ 5.25
Operating costs	<u>3.06</u>
Operating margin	\$ 2.19
Operating margin per year	\$ 15,636,600
Royalty (10 percent NSR)	<u>3,061,275</u>
Operating margin after royalty	\$ 12,575,325
Depreciation	5,710,215
Depletion	<u>3,432,555(1)</u>
Texable income	\$ 3,432,555
Income taxes @ .53	1,819,254
Operating margin (after royalty)	\$ 12,575,325
Less income tax	1,819,254
Less depreciation	<u>5,710,215</u>
Net Profit	5,045,856
Plus depreciation	<u>5,710,215</u>
Cash flow to operations	10,756,071
10 percent of NS as percent of Net Profit (2)	61 %

Assume Royalty as 30 percent of net Profit - this would be approximately 6 percent of NSR at 60 ¢ copper.

The allowable depletion under U.S. tax laws for copper is 15 percent of the net smelter value (sales value of the concentrate less freight, smelting and refining charges) but is limited to 50 percent of the net profit (operating margin less depreciation).

The amount of depletion for copper ores is calculated as 15 percent of the gross value or 50 percent of the net profit; the lesser value must be used.

Example

NSR = \$ 30,612, 750

Depletion Calculation

1. 15 percent of NSR
 $30,612,750 \times .15 = \$ 4,591,912$

2. 50 percent of net profit

Operating margin (after royalty) =	\$ 12,575,325
Less Depreciation	- 5,710,215

Net Profit	\$ 6,865,110
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$6,865,110 \times .50 = \$ 3,432,555$

In this example, 50 percent of net profit is the lesser amount and must be used.

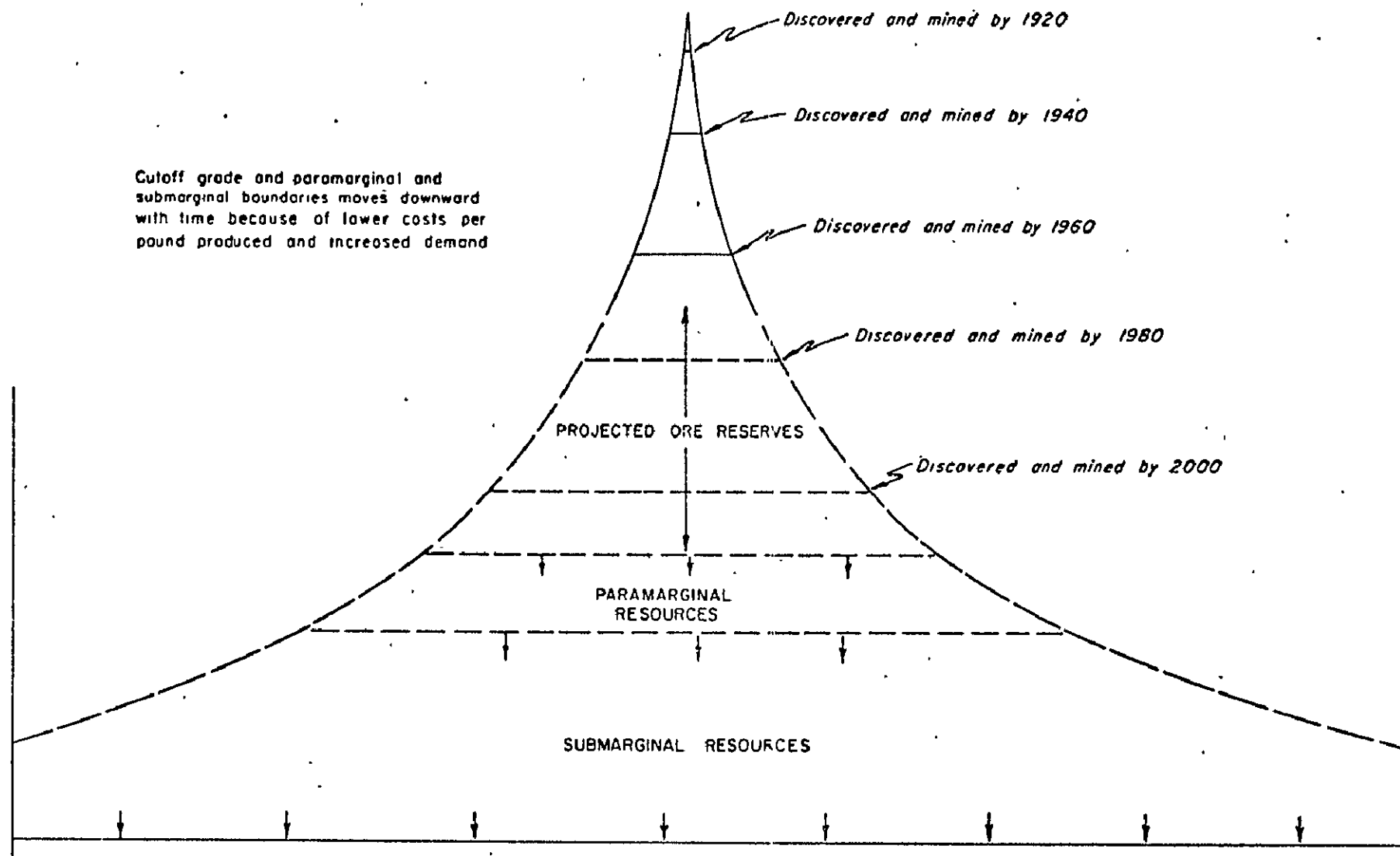
MINERAL RESERVES VS MINERAL RESOURCES

Long term ore reserves are limited in most metals and mineral commodities in the United States, which is rapidly becoming a deficient nation in many. In others, paramarginal and submarginal resources are extensive, but their value over the long term will be dependent on improved technology to lower production costs, on rising prices in relation to costs resulting from world wide shortages in each metal or mineral commodity and world politics.

Copper is a metal of which the United States has an adequate supply in the near term largely because of improved technology in exploitation, beneficiation, smelting and refining and in fabricating the copper into marketable products. Plate Z' illustrates the history of large scale copper production in the United States. In 1915 the first large, low grade operation was started by Jackling and his associates at Bingham Canyon close to Salt Lake City. A 1500 ton plant was constructed to treat 1 1/2 percent porphyry copper ore. No one believed it could be successful. It not only was a success, but today over 100,000 tons of ore are mined and treated each day at Bingham, an indication of great advances in all aspects of the copper industry. Today the grade of the ore is approximately 1/4 of one percent. Continued improvements in technology no doubt will continue to allow much lower grades of ore to be produced. If so, the extensive paramarginal and perhaps some of the submarginal reserves of copper in the porphyry copper deposits of the western United States will become economic.

IDEALIZED CONE PROJECTION OF THE PORPHYRY COPPER RESOURCES OF THE UNITED STATES

Cutoff grade and paramarginal and submarginal boundaries moves downward with time because of lower costs per pound produced and increased demand



APENDIX I.

GEOLOGICAL ENVIRONMENTS OF MASSIVE SULFIDE DEPOSITS IN TASMANIA

by

R. W. HUTCHINSON

Important massive sulfide orebodies of three neighboring districts in western Tasmania provide an interesting contrast in composition and geological environment, and a significant comparison with Canadian examples. Deposits in all three districts are stratabound and occur in eugeosynclinal successions of mid- to upper-Cambrian age, deposited during early stages of Tasman belt orogenic evolution. Two of the districts lie within the major Mount Read volcanic arc which was flanked to the west by the deep Dundas trough, in which the third district is located.

In the Mount Lyell district both massive pyrite-chalcopyrite lenses and larger underlying deposits of stringer-disseminated sulfides occur in highly schistose felsic metavolcanic rocks. These copper-rich volcanogenic ores were formed in a major, domal centre of explosive, felsic volcanism. In the Read-Rosebery district, 20 miles farther north along the volcanic arc, lenses of wellbanded, pyritic, Zn-Pb-Cu rich sulfide with barite gangue occur in more regularly stratified pyroclastic and volcanoclastic sedimentary rocks. These volcanogenic sulfides and their host rocks were deposited in a somewhat deeper and more distal volcanic environment. Deposits of the Renison Bell tinfield are stratabound lenses of cassiterite-bearing massive pyrrhotite closely associated with deep, discordant fractures containing both cassiterite and base metal sulfides. They occur in deep water, basinal sedimentary rocks of the Dundas trough but at a change from shelf to eugeosynclinal sedimentary lithofacies. This stratigraphic horizon may be correlative with the volcanic rocks in the arc to the east. Although not previously so interpreted, these deposits may be of volcanogenic origin.

Thus it appears that copper-rich volcanogenic deposits form in domal centres of explosive felsic volcanism, whereas zinc-lead rich bodies prefer somewhat deeper volcanic basins of more regularly stratified flows and pyroclastic-volcanoclastic deposition. A Canadian counterpart is the Noranda district where the Horne and Quemont bodies represent the former environment, the Waite-Amulet-Dufault-Vauze bodies the latter. It is significant that still other volcanogenic deposits, like Renison Bell, occur not in the volcanic environment currently so heavily emphasized in exploration, but in deep eugeosynclinal troughs.

Abstract pub. in program of Annual General Meeting, Can. Inst. Min. Met. Bull., March, 1975.

APENDIX 2.

MASSIVE BASE METAL SULFIDE DEPOSITS IN SEDIMENTARY ROCKS AND THEIR METALLOGENIC RELATIONSHIPS DURING PROTEROZOIC TIME

by

R. W. HUTCHINSON

Certain Proterozoic mineral deposits may be characteristic and related through evolutionary changes in environment, to their more primitive Archean forerunners. Based on distinctive deposits the Proterozoic Epoch may be divisible into two metallogenic subepochs, Aphebian and Helikian-Hadrynian.

Archean volcanogenic massive sulfide deposits bearing copper and zinc are spatially and perhaps genetically related to magnetic iron formations and certain gold deposits. In Aphebian time lead, with significant silver, becomes important in volcanogenic massive sulfides, accompanying zinc and copper. Gold, although present, is more abundant in the important quartz pebble conglomerates. Hematitic iron formations are characteristic of mid-Aphebian rocks around the world.

In contrast, important base metal sulfide deposits in younger Helikian-Hadrynian rocks occur in metasedimentary argillites, graywackes and siltstones, not therefore directly volcanogenic but probably exhalative sedimentary related to sea floor fumaroles. They are distinctively rich in zinc, lead and silver but deficient in copper, which, however, occurs for the first time in important sedimentary deposits.

With thickening crust the abundant, primitive subaqueous volcanism of Archean time evolved toward more restricted, shallower subaqueous or subaerial volcanism in Aphebian time. Subsequently, rifting in Helikian-Hadrynian time was accompanied by gaseous emission in the medial parts of the rifts and possibly by subaerial basaltic eruptions along their margins. Fumarolic activity accompanying each style of volcanism generated the differing varieties of base metal deposits. This crustal evolution, with concomitant hydrospheric-atmospheric evolution from reducing to oxidizing conditions, also favored the formation of Aphebian sedimentary conglomeratic gold ores and hematitic iron formations.

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APPENDIX 3.

RELATIONSHIPS BETWEEN MASSIVE SULPHIDES AND PORPHYRY COPPER DEPOSITS

by

R. W. HUTCHINSON and R. W. HODDER

Pyritic massive sulphide deposits lie conformably above submarine volcanic rocks, and beneath siliceous and manganiferous iron formation. The massive bodies are often zoned with a barren pyritic top grading downward into pyrite with sphalerite, and occasionally galena, and a chalcopyrite-rich base. They are frequently brecciated like the lavas beneath them, which contain pyrite and chalcopyrite as coatings on joints and fractures, and as disseminations. The lavas also exhibit intensive propylitic, argillic, and siliceous alteration. These deposits apparently formed on sea bottom from fluids escaping through the lavas during periods of subaqueous, exhalative and sometimes explosive volcanism. The process may be comparable to deposition of base metals from hot brines in the Red Sea deep.

Some porphyry copper deposits resemble the altered, sulphide-impregnated lavas beneath the massive sulphides. In porphyry copper deposits, pyrite and chalcopyrite occur as veinlets and dispersed grains in intensely fractured tuffs, flows, sub-volcanic intrusions or other host rocks, characterized by propylitic, argillic, and siliceous alteration. Metal zoning is present; sphalerite and galena often occur in manganiferous veins peripheral to a pyritic shell and a chalcopyrite-bearing interior. These deposits apparently formed from hydrothermal fluids escaping, either passively or violently, from solidifying magma. The fluids may be comparable to hot brines of the Salton Sea in California.

There are also important differences between the two types of deposits. The massive sulphides occur in differentiated, mafic-to-felsic submarine lavas, whereas the porphyry deposits are associated with shallow plutons and subareal volcanic rocks of intermediate to felsic composition. Calcic-sodic metasomatism accompanies the massive sulphides, whereas that in the porphyry deposits is dominantly potassic. Further, ages of massive sulphides range from Archean (Keewatin) to Tertiary, but porphyry copper date from early Triassic to late Tertiary.

These similarities and differences suggest that massive sulphide and porphyry copper deposits are related. The former were generated during primitive stages of crustal evolution, particularly in Archean time, and were repeatedly derived during primitive stages of younger, individual tectonic cycles. In contrast, the porphyry coppers were developed during later, more mature stages of crustal evolution, in terms of both absolute age and relative age within younger individual tectonic cycles. Rather than being of early magmatic, eugeosynclinal affiliation, as are the massive sulphides the porphyry deposits formed in late-magmatic, predominantly subvolcanic settings at the edge of thick continental plates, where exhalative volcanism was a subareal phenomenon.

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